

No. II

1924

# THE JOURNAL

OF THE

## IRON AND STEEL INSTITUTE

VOL. CX.

EDITED BY

GEORGE C. LLOYD

SECRETARY



PUBLISHED AT THE OFFICES OF THE INSTITUTE  
28, VICTORIA STREET, LONDON, S.W. 1.

AND BY

E. & F. N. SPON, LIMITED, 57, HAYMARKET

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1924

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## PREFACE.

THE present volume of the *Journal of the Iron and Steel Institute* contains eleven papers presented at the Autumn Meeting, held at the British Empire Exhibition, Wembley, London, with the discussions and correspondence thereon. Amongst these will be found the first instalment of an important investigation on the alloys of iron carried out at the National Physical Laboratory, under the auspices of the newly formed "Alloys Research Committee."

Biographical notes of the careers of Members deceased will be found under "Obituary Notices."

Section II. contains, as usual, notes on the progress of the home and foreign iron and steel industries, as reported in the proceedings of scientific and technical societies and in the technical press, together with a short review of new books presented to the Institute, and a bibliography of the principal works dealing with the metallurgy of iron and steel and allied subjects, which have appeared during the past six months.

At the end is inserted a list of the British Standardised Steel Samples issued jointly by the Iron and Steel Institute and the National Physical Laboratory showing where and on what terms they are available.



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# THE IRON AND STEEL INSTITUTE.

## SECTION I.

### *MINUTES OF PROCEEDINGS.*

#### AUTUMN MEETING.

THE AUTUMN MEETING of the IRON AND STEEL INSTITUTE was held at the British Empire Exhibition, Wembley, on Thursday and Friday, September 4 and 5, 1924, Sir WILLIAM ELLIS, G.B.E., D.Eng. (President), occupying the Chair.

On the opening of the proceedings at 10.30 on the morning of Thursday, September 4, 1924, the Minutes of the last Annual Meeting, held in London in May, were taken as read and confirmed.

Mr. A. HARVEY (London) and Mr. W. CROSS (London) were appointed scrutineers of the ballot for the election of new members, and on their completion of the scrutiny announced that the following candidates had been duly elected :

#### MEMBERS.

NAME.	ADDRESS.	PROPOSERS.
Adam, Alastair Thomas	14 Links Place, Musselburgh	J. D. Brunton, J. Craig, G. P. West.
Astbury, Samuel John, M.A. (Cantab.)	N. Hingley & Sons, Ltd., Netherton Ironworks, Dudley	J. E. Fletcher, J. S. Trinham, P. Jump.
Bagna, Giuseppe	42 Via Piffetti, Turin, Italy	G. A. V. Russell, G. M. Brown, E. H. Saniter.

NAME.	ADDRESS.	PROPOSERS.
Banks, Francis William Richard	The Dell, Barnt Green, Birmingham	Sir William Ellis, G.B.E., Sir Frederick Mills, Bart., H. B. Toy.
Burch, Charles S.	Bark Hart, Orpington, Kent	G. Hatton, C.B.E., J. S. Trinham, J.W. Trows- dale.
Carosio, Ing. Giovanni, M.I.Mech.E.	Via Monte Napoleone 22, Milan	R. T. Durran, Sir James Kemnal, Sir R. A. Hadfield, Bart.
Cervera, José M.	Apartado 4, San Fer- nando, Spain	A. C. Dalton, T. H. Watson, W. J. Daw- son.
Deschamps, Joseph	The Coppice, Letchworth, Herts.	H. G. Stobart, C. P. Sandberg, T. H. C. Homersham.
Dickson, Henry Charles	Halesowen Steel Co., near Birmingham	G. Hatton, C.B.E., J. S. Trinham, J.W. Trows- dale.
Elam, Miss Constance F. M.A. (Cantab.)	Addington House, New Barnet	H. C. H. Carpenter, N. Belaiew, G. D. Ben- gough.
Elliot, Ian Frederick Lettsom	66 Cannon Street, London, E.C. 4	F. W. Keen, T. S. Pea- cock, W. Simons.
Fernandez, Ismael	Calle Hortalizas 30, Gijon, Asturias, Spain	A. de Churruca, V. Balanzategui, L. Bar- reiro.
Fraser, James, C.M.G., M.Inst.C.E.	Commissioners' Office, New South Wales Government Railways & Tramways, Sydney, N.S.W.	D. J. Shedden, J. H. Skelton, J. E. Latham.
George, Jerome R.	54 Elm Street, Wor- cester, Mass., U.S.A.	A. Peech, A. J. Capron, T. W. Hand.
Gibney, James Louis	416 Woodward Avenue, Buffalo, New York, U.S.A.	H. B. Hanley, A. Sau- veur, E. L. Reed.
Hamilton, Forman	1420, 4th Avenue, Cora- opolis, Pa., U.S.A.	J. A. Coyle, W. J. Green, S. S. Green.
Hann, Frank Percival	Llangattoch Park, Crick- howell, Breconshire	Sir Frederick Mills, Bart., Sir William Ellis, G.B.E., F. Samuelson.
Henry, Curtis Raymond	United Alloy Steel Cor- poration, Canton, Ohio, U.S.A.	M. H. Schmid, R. S. Poister, T. H. Nelson.
Johnson, George Henry	Linthorpe, Rockingham Road, Kettering	A. McBean, A. Cooper, C. H. Ridsdale.
Klang, Max, LL.D.	10 Rue Victorien Sardou, Paris (16°)	P. Keim, P. Gouge, D. C. Lysaght.
Lee, Dai Chin	25 Sha-Ho-Kai, South Gate, Changsha, Hunan, China	A. Sauveur, G. B. Water- house, E. L. Reed.
Lewis, W. Walker	Pinners Hall, Old Broad Street, London, E.C. 2	Sir R. A. Hadfield, Bart., A. B. H. Clerke, P. B. Brown.



NAME.	ADDRESS.	PROPOSERS.
McBean, Archibald D. G.	Tynninghame, Tettenhall, Wolverhampton	A. Cooper, A. McBean, J. Payton.
Matsushita, Tokujiro .	Research Institute for Iron, Steel, and other Metals, Sendai, Japan	K. Honda, H. C. H. Carpenter, Sir R. A. Hadfield, Bart.
Nepper, Fernand .	Fabrique Nationale d'Armes de Guerre, Soc. Anon., Herstal-lez-Liège, Belgium	A. Galopin, H. de Gorski.
Nield, George William .	The Jamshedpur Steel-works, India	James Henderson, A. Robinson, H. E. Wright.
Olazabal, Luis de .	Rodríguez Arias No. 1-4 <sup>o</sup> , Bilbao	A. de Churruga, V. Balanzategui, L. Barreiro.
Roure, Jerónimo .	Apartado 13, Bilbao	Sir Ramon de la Sota, K.B.E., L. M. de Aznar, E. de Aburto.
Singh, Lachhman, A.M.Inst.C.E.	Phagwara, Panshta, Punjab, India	Sir William Ellis, G.B.E.
Stuck, Harold D. .	184 Abbott Street, Lawrence, Mass., U.S.A.	V. O. Homerberg, E. A. Mead, I. N. Zavarine.
Van der Waerden, J. .	12 Carol van Bylandtlaan, The Hague, Holland	V. B. Reichwald, H. E. Oving, jun., E. Bury.
Wildsmith, George Hector Robert	Petersfield, Yarborough Road, Lincoln	G. T. Wildsmith, S. Widdas, E. Adamson.
Williams, Edgar .	Beaumont, Mount Pleasant, Swansea	F. T. Thomas, J. Davies, T. O. Lewis.
ASSOCIATE.		
Sen, Nalinbihari, B.Sc.	221 Cemetery Road, Sheffield	C. H. Desch, T. F. Russell, E. Gregory.

## CHANGES IN THE COUNCIL.

The PRESIDENT said it was usual at an Autumn Meeting for the President to make some announcement as to the changes that had occurred on the Council since the previous meeting. The Council had appointed four gentlemen—Vice-Presidents and Members of Council—to the position of Honorary Vice-Presidents, namely, Professor H. L. Le Chatelier, who was so well known for his scientific work ; Mr. William H. Hewlett ; Mr. Edward Steer ; and Mr. C. J. Bagley. He desired, in the name of all the members, to express their regret that the Institute would not have the services of any of those gentlemen as its President. There were

two reasons for that state of affairs—the first, a very substantial one, that of age, and the second, the onerous duties and responsibilities which those gentlemen bore at the present moment. It would be bad taste on his part to allude, except very casually, to a subject to which he had referred on a previous occasion—namely, that he hoped the new rule which the Council had introduced of the Presidency being held, except in very unusual circumstances, for one year only, might obviate in future the loss of the services of such eminent men as those he had mentioned. He thought the members would agree that all the gentlemen to whom he had referred were eminently suitable to occupy in turn the position of President of the Institute, and it was because they were no longer able to take the office of President that the Council had endeavoured to honour them by electing them as Honorary Vice-Presidents. He hoped the helpful interest they had taken in the work of the Institute would not be lessened, but would be increased by the effort which had been made to honour them in the manner he had announced.

#### PRESIDENT ELECT.

He further had much pleasure in announcing that a gentleman who was well known in the steel industry, and also for the valuable work he had done for the Institute, had accepted the office of President for the coming year—namely, Sir Frederick Mills, Bart. In view of the elections to which he had referred, certain vacancies had been created in the list of Vice-Presidents, and the Council had accordingly elected the following three gentlemen to be Vice-Presidents of the Institute: Colonel Sir Charles Wright, K.B.E., C.B.; Mr. Frank W. Harbord, C.B.E.; and Mr. William R. Lysaght, C.B.E. Consequent on those elections, vacancies had occurred in the Council, which it was proposed to fill by the appointment of Dr. C. H. Desch, F.R.S., a very eminent metallurgist; Captain Valentine Beardmore Stewart, C.B.E., a colleague of Lord Invernairn; and Mr. William Simons.

Continuing, the President said that although the Institute existed for the purpose of studying the technical side of the iron and steel industry, it was impossible for members to fail to take notice of the serious position in which the iron and steel industry

found itself at the present time. It was true that was a commercial question, but it was so closely associated with their efforts as members of the Institute that he thought he was in order in basing some remarks upon a fact which, unfortunately, they all knew too well. It appeared to him that there never had been a time when the valuable services of members of the Institute, possessing, as they did, special technical knowledge resulting from years and years of close scientific study, would be appreciated more fully than in connection with the position in which the industry found itself. It was up against certain economic difficulties, apart from financial ones, which were almost staggering. It was true that there were other countries which, happily, had been able to spend more money on plant and renewing the general equipment of their works than had been possible in Great Britain since the war, owing to the stringent financial conditions that had existed. He desired, however, to urge very strongly that, whatever the financial difficulties in Great Britain might be, they would be increased rather than lessened if those responsible in connection with steel plants failed to realise the great importance of maintaining those plants on as modern lines as possible. It was most important for those at the head of concerns to listen attentively to the proposals and criticisms which were put forward by the members of their staffs, whether those members were metallurgists or engineers, because he felt quite certain that, in view of the difficult circumstances to which he had alluded, the industry could only exist in competition with other countries if plants and appliances were put into absolutely modern conditions, and all the labour-saving and fuel-saving ideas which were put before them were adopted. In that connection he desired to plead for the younger men, both in engineering and metallurgy, many hundreds of whom, as was well known, were thoroughly well equipped on the technical side of their subjects. He knew that such men coming into works without any practical knowledge, or with very little practical knowledge, might be regarded as to some extent a danger. He desired, however, to urge, as a perfectly sound point, that the steel-maker and the maintenance engineer, both of whom were very well equipped with practical knowledge, were from day to day carrying on not only the manufacturing processes but all

the administrative work, and it was practically impossible for men in such a position to give the necessary time and to bring perhaps the latest knowledge to bear in connection with the economic adjustment, either of machinery or of metallurgical processes, which they might do were they less burdened with routine work. On the other hand, if advantage were taken of the knowledge of younger men of good scientific training, who were well-read in all modern economic methods which had recently been put forward by eminent men, it would be possible for them to make suggestions to the head men as to how economies in fuel, in furnaces, in machinery, in electric driving, and in other directions, could be introduced, and that would result in obtaining much better and more valuable work from the men in command of the metallurgical and engineering sides. Much spadework would thus be done by younger men with modern educational equipment, thus lessening the amount of preparation work and reading involved in arriving at a sound opinion on the desirability or otherwise of introducing various economies. He felt certain that if Great Britain were to live in competition with some of its foreign neighbours it would be necessary to look very closely into the question of rendering available the scientific and educational advances which had been made in connection with steelworks machinery, whether on the engineering side, the fuel side, or the metallurgical side. He thought members of the Institute ought to take most carefully into account that aspect of affairs, realising that in many cases the industry was actually fighting for its very existence.

The authors of the papers "On the Nature of High-Speed Steel," and "The Changes of Volume of Steels during Heat Treatment," which were announced as the first papers to be read, not being present, it was decided to proceed with the paper by Professor EDWARDS on "Pickling; or the Action of Acid Solutions on Mild Steel and the Diffusion of Hydrogen through the Metal," after which a paper on "The Effect of Free Surfaces on the Plastic Deformation of Certain Metals," by F. C. THOMPSON, D.Met., B.Sc., and W. E. W. MILLINGTON, M.Inst.C.E., M.I.Mech.E. (Manchester), was read, and the meeting adjourned to the following day.



On the morning of Friday, September 5, the PRESIDENT formally announced that, in accordance with Rule 10, the following list of Vice-Presidents and Members of Council due to retire at the Annual Meeting, 1925, was submitted to the Council. The Vice-Presidents retiring were the following: Mr. Andrew Lamberton, Sir Charles Wright, and Mr. Mannaberg; and the Members of Council retiring were Mr. Charles Markham, Mr. G. Hatton, Mr. B. Talbot, Mr. H. Brearley, and Professor H. Louis.

The gentlemen whose names had been read out were eligible for re-election at the Annual Meeting if no other names were received within one month of that meeting.

The following papers were then read :

“Ferrous Alloys Research. Part I.—Introduction,” by WALTER ROSENHAIN, D.Sc., F.R.S. (National Physical Laboratory).

“Part II.—Iron and Oxygen,” by FRED. S. TRITTON and D. HANSON, D.Sc. (National Physical Laboratory).

“Part III.—The Estimation of Oxygen in Pure Iron,” by T. E. ROONEY, A.I.C., A.M.S.T. (National Physical Laboratory), and

“The Hardening of Steel,” by WALTER ROSENHAIN, D.Sc., F.R.S., F.Inst.P.

After the first-named paper had been discussed and Dr. Rosenhain had introduced the paper standing in his own name,

The PRESIDENT said that in view of the shortness of the time available for discussion of the papers, it was necessary for him to announce that, with Dr. Rosenhain's consent, it had been arranged that any discussion on Dr. Rosenhain's paper would take place by correspondence. That was largely due to the fact that the next paper to be read was by Dr. Axel Hultgren, who had come over from Sweden specially to read his paper, and it would therefore be very discourteous not to allow him a full opportunity of placing his views before the meeting. He begged to move a most hearty vote of thanks to Dr. Rosenhain for his instructive paper.

The resolution was carried by acclamation.

The following paper was then read :

“Improvements in the Brinell Test on Hardened Steel, Including a New Method of Producing Hard Steel Balls,” by AXEL HULTGREN, Met.Eng. (Gothenburg).

After Mr. Hultgren's paper had been discussed,

Sir ROBERT HADFIELD, Bart., F.R.S. (Past-President), moved a hearty vote of thanks to the President for the admirable manner in which he had presided over the meeting, and said the members were specially indebted to Sir William Ellis for the manner in which he had conducted the proceedings during the past two days. They would also desire to thank him most cordially for presiding so admirably over the important meetings of the Empire Mining and Metallurgical Congress, which had been held during the summer, at Wembley.

The resolution of thanks having been carried by acclamation,

The PRESIDENT, in reply, said he was exceedingly indebted to the members for the kind vote of thanks they had passed. He thought they ought to go away from the meeting very satisfied with the interest which had been shown in the papers. At one time the Council were a little apprehensive lest the fact that the Mining and Metallurgical Congress held in June might lessen the interest in the Autumnal Meeting. The large attendances at the meeting, the interest taken in the papers, and the importance of the discussions that had ensued showed that the Congress had not interfered in any way with the success of the Autumn Meeting.

The meeting then terminated.

## Iron and Steel Institute.

### PICKLING ; OR, THE ACTION OF ACID SOLUTIONS ON MILD STEEL AND THE DIFFUSION OF HYDROGEN THROUGH THE METAL.

BY PROFESSOR C. A. EDWARDS, D.Sc. (SWANSEA).

As is well known, the oxide of iron which is formed on the surface of steel during hot-rolling, &c., has to be completely removed before the metal can be satisfactorily covered with a superficial coating of tin, zinc, or enamel. This is because it is essential to have a perfectly clean metallic surface before tin, or zinc, will unite with the steel, or enamel can form an adherent coating upon it. In the trades, the operation in which this cleaning is performed is known as "pickling." The steel is immersed in aqueous solutions of sulphuric or hydrochloric acid. The acidity of the solutions used varies within wide limits, and depends upon the amount of oxide which has to be removed, and to some extent upon the nature of the coating it is subsequently intended to put upon the metal. The acid penetrates the more or less porous film of oxide, and on coming into contact with the underlying metal forms ferrous sulphate, or ferrous chloride, as the case may be, with the liberation of hydrogen. In spite of what some writers on this subject have said, there can be no doubt that this gas, being generated, as it is, between the metal and the oxide, is responsible for the removal of a large proportion of the oxide by mechanically detaching it from the metal before it can be dissolved by the acid. Other reactions may also take place, but for the purpose of the present paper only one need be mentioned.

In a general kind of way it has long been known that not the whole of the hydrogen generated by the action of sulphuric or hydrochloric acid upon steel freely escapes from the liquid ; some is taken up—that is, absorbed—by the metal itself, and is more or less permanently retained in that condition. Further, it is recognised that when hydrogen has been absorbed by steel in this manner the metal is embrittled. Some of this embrittling can only

be regarded as of a temporary character, for it can be removed by a low-temperature annealing. The revival of the properties of the metal, by this annealing, is due to a large proportion of the absorbed hydrogen being driven out of the metal. The amount of hydrogen which can be removed in this way is governed by two factors—namely, time and temperature of annealing. The higher the temperature and the longer the time, the more complete the elimination of the hydrogen.

After a careful search in the literature bearing on this subject, the earliest reference to the above phenomena which the author has been able to locate is by Cailletet.<sup>(1)</sup> This work does not appear to be generally known, and the present investigation was almost completed before the author came across it. Cailletet found that some of the hydrogen generated during pickling is not only absorbed by the iron, but that the gas will readily diffuse through the metal, and can be collected at the opposite surface. Further, he also demonstrated that this diffusion will proceed against a pressure of fourteen atmospheres. Quite independently, W. H. Johnson<sup>(2)</sup> made some interesting observations concerning the absorption of hydrogen by iron, and arising out of these Osborne Reynolds<sup>(3)</sup> demonstrated in a very simple manner that hydrogen will diffuse through wrought iron. He says: "I then obtained a piece of wrought iron gas pipe 6 inches long and  $\frac{5}{8}$  inch external diameter, and rather more than  $\frac{1}{16}$  inch thick; I had this cleaned in a lathe, both inside and outside; over one end I soldered a piece of copper so as to stop it, and the other I connected with a piece of glass tube by means of india-rubber tube. I then filled both glass and iron tubes with olive oil and immersed the iron tube in dilute sulphuric acid; . . . with a view to increase the speed (of diffusion) I changed the acid several times without much effect, until I happened to use some acid which had only just been diluted and was warm; then the gas came off twenty to thirty times as fast as it did previously. I then put a lamp under the bath and measured the rate at which the gas came off, and I found that when the acid was at the point of boiling as much hydrogen was given off in five seconds as had previously come off in ten minutes, and the rate was maintained in both cases for several hours." The same investigator also gave evidence showing that the hydrogen absorbed during pickling is slowly eliminated from



the steel at ordinary temperatures, but much more rapidly at 100° C. Judging from the work done by Cailletet, and by Osborne Reynolds, there can be no doubt that the more essential features concerning this particular aspect of pickling were known over fifty years ago, and it is therefore all the more surprising that so little quantitative evidence has since been published.

In recent years a considerable number of researches have been published which deal with the effects of cathodically liberated hydrogen on the properties of the steel, and the influence of current density on the rate at which hydrogen diffuses through the metal. Amongst these may be mentioned that by F. S. Fuller,<sup>(4)</sup> who showed that hydrogen will pass through iron at temperatures from 20° to 100° C., both when the metal is pickled directly in 1·0 per cent. solution of sulphuric acid and when it is made the cathode in such acid. In this work no attempt was made to study the effects of acidity, and varying temperatures, upon the rate of diffusion; it was almost entirely concerned with the effects of current density on the diffusibility of hydrogen, &c.

In 1922 G. C. Schmidt and T. Lucke<sup>(6)</sup> gave an account of a most interesting series of experiments in which they studied the change of potential, with time, whilst the current was passing through the electrolyte, and after the current had been discontinued.

A little later M. Bodenstein<sup>(7)</sup> worked in a similar direction, and concluded that cathodically generated hydrogen diffuses through iron in the atomic state. In an attempt to demonstrate that the gas was in the atomic condition he hoped to make it combine with bromine vapour, chlorine, or sulphur, on withdrawing it from the interior of the cathode, but met with no success. With nitrogen, however, a small quantity of ammonia was formed, and with oxygen large quantities of water.

Numerous papers dealing with the embrittling effects of hydrogen on iron and steel, both by ordinary pickling and when the gas is cathodically generated, have been made. Since, however, the present paper does not deal with this aspect of the question, those interested are referred to the original publications, and especially to the papers by Fuller<sup>(4), (5)</sup> and by S. C. Langdon and M. A. Grossman,<sup>(8)</sup> in which full references are given.

The present author's attention was drawn to this question on

taking up the study of the defect known as "peppery blisters," which is sometimes encountered in the manufacture of tinplates. These blisters are extremely small, and appear on the finished sheet in large numbers, giving the surface a pimpled and rather dull appearance.

Dealing with this subject in 1901, Ridsdale<sup>(9)</sup> said: "Pickling may sometimes cause blisters on thin sheets. These pickling blisters are quite distinct from ordinary blowhole blisters, and are usually thickly distributed over the plate. They never appear until after pickling, and often come up after the annealing which follows it. Such blistered sheets are also brittle." He stated that he had sheared blistered sheets into shreds, under water, and collected the liberated gas, which consisted essentially of hydrogen. From the point of view of the present investigation, the two most interesting conclusions which Ridsdale put forward were:

- "(1) It seems probable that the grains, which in thin sheets are flattened into flakes or laminæ, become separated perhaps by the action of the acid, and when sufficiently thin the film of metal is disturbed by the hydrogen either at once or by the heat whilst annealing."
- "(2) He had never seen conclusively explained why, or under what conditions, the hydrogen is absorbed, whether it is a question of strength of acid, temperature, or length of time, but it is quite certain that pickling does not always have the same effect."

Some idea of the character of the blisters under consideration may be gained from an examination of the photomicrographs Figs. 1 to 5 (Plates I. and II.) of unetched cross-sections of peppery blistered tinplates. As will be seen, they are small and vary very much in shape. So far it has not been possible to ascertain the nature of the substance present in the plates at the areas which correspond with these holes, but before they were developed by pickling, &c.

E. F. Law<sup>(10)</sup> conducted some useful experiments relating to these blisters, from which he concluded that:

"Oxidised steel will give rise to blistered sheets, and that this defect is more liable to occur with Bessemer than with

open-hearth steel." He offers the following explanation of the formation of these blisters :

" . . . in the pickling bath large volumes of hydrogen are evolved, and it is well known that hydrogen is capable of entering and passing through a thin sheet of steel. Further, nascent hydrogen is a powerful reducing agent, and this hydrogen, assisted by the high temperature of the pickling bath, reduces the oxide in the steel with the formation of water vapour. The volume of the molecule of water is, however, much greater than that of hydrogen, and, therefore, is incapable of passing out of the sheet. Moreover, the volume occupied by the water vapour is much greater than the volume occupied by the original oxide, and the internal pressure thus produced is sufficient to cause an incipient blister, which increases in size, owing to the expansion of the water vapour when the sheet is subsequently annealed. During the annealing, however, the reaction is reversed, for at a red heat water vapour is again decomposed, with the formation of oxide and the liberation of hydrogen."

Prior to making any of the experiments which are to be described in the present paper, the author formed the view that there was another explanation which would fit in with all the facts quite as well as the one put forward by Law.

Whilst agreeing that isolated patches of oxide might give rise to blisters, it does not seem necessary to postulate that reduction of this oxide need take place. Indeed, to the author it seems just as conceivable that undissolved impurities, or constituents such as carbide of iron and manganese sulphide, might behave in precisely the same manner as oxide of iron in this respect. Taking the fact that hydrogen has the power of diffusing through iron, it may be assumed that this diffusion will naturally continue until the metal becomes saturated with the gas. The saturation limit will no doubt vary with the temperature and strength of acid used. With perfectly pure iron this diffusion and saturation of the metal is probably brought about by the hydrogen atoms being, so to speak, passed from one atom of iron to another, until the former is uniformly distributed through the metal. Commercial steels cannot, however, be perfectly homogeneous in this sense, and some are less so than others. If it be assumed that the small dots in Fig. 8 represent atoms of iron, and the area X is an inclusion of some

kind which is not iron, then, during pickling, the hydrogen atoms would enter at the surfaces *a* and *b*, and would be conveyed along the path of the iron atoms until they reached the boundary of X. At this stage further diffusion would be obstructed by the inclusion, and the hydrogen atoms reaching this surface would be forced to detach themselves from those of iron by the continuous

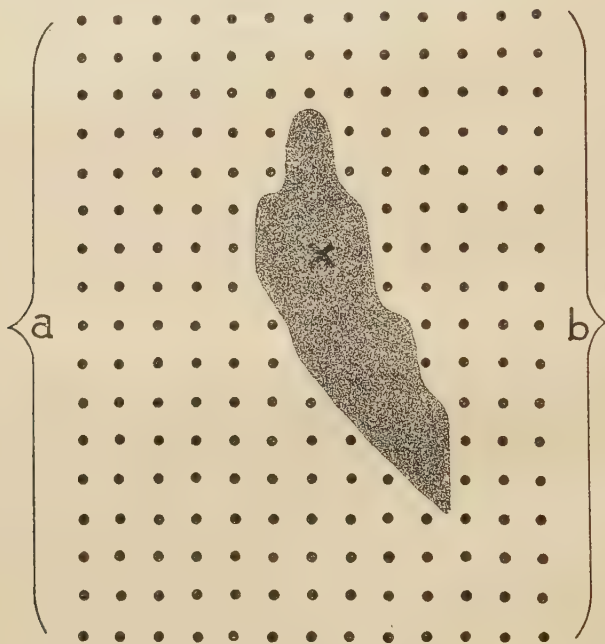


FIG. 8.

flow of hydrogen from behind. As these hydrogen atoms become detached they would form molecules  $H_2$ , which of course are incapable of diffusing through iron at ordinary temperatures. Hence molecular hydrogen would accumulate at the boundary of X, and the amount of this entrapped gas would go on increasing, because the inflow would continue so long as pickling was in progress ; the rate of inflow being scarcely, if at all, affected by the increasing internal pressure. Naturally, the thinner the plate, or the nearer the inclusion to the surface, the shorter will be the time required for the hydrogen to penetrate to such inclusions. In



very thin plates the internal pressure at these inclusions will quickly become so great as to cause a blister by forcing out the surfaces of the sheet, even at ordinary temperatures, or at something below  $100^{\circ}$  C. But, even if the pressures be not high enough to do this by the end of the pickling operation, there is a further opportunity during white annealing, or when the sheets are being passed through the tinning bath. This is a very simple explanation; but it must be confessed that it would be more acceptable if experimental facts could be obtained that would carry it a little beyond the stage of pure speculation. It was a difficult matter to see how this could be done by planning experiments that would be conclusive, or even definitely helpful. The most difficult thing to arrange in this respect was, to have an inclusion in a known position without cutting the specimen to find it. After much consideration, and many attempts of different kinds, a very simple and satisfactory test, so far as oxide of iron is concerned, was devised.

To make this clear, it will be useful briefly to draw attention to a few facts relating to the manufacture of tinplates. In rolling, after the original bar has been hot-rolled in the sheet-mill for a number of passes, the sheet is doubled, reheated, and the doubled sheet again hot-rolled. This operation of doubling, &c., is repeated until the thickness of the sheet has been reduced to the desired degree. As these rolling operations are carried out at a good red heat, each sheet in the finished bundle is separated from its neighbours by a film of oxide of iron. The success of subsequently opening, that is, separation of these sheets from one another, after shearing the folded edges, depends almost entirely on whether the film of oxide between the sheets has remained continuous or not. If the film has become broken during rolling, welding at such points might occur, and complete separation becomes difficult, if not impossible.

It will thus be seen that by taking two sheets of this kind, which have not been disturbed since hot-rolling, it ought to be possible to get an oxide inclusion, in a known position, and study the effect of pickling upon it. Fig. 6 (Plate III.) shows a photomicrograph of an oxide film between two sheets. With this in view, a large number of compound sheets have been examined. For this purpose circular discs 3 inches diameter were cut out

and the edges carefully welded together by means of an oxy-hydrogen flame, thus sealing up the two plates and obtaining an inclusion of oxide of iron. The thickness of the discs was 0.46 millimetre—that is, each sheet was 0.23 millimetre thick minus half the thickness of the oxide film.

On immersing these specimens in aqueous solutions of sulphuric or hydrochloric acid of any strength up to 30 per cent. acidity, and at any temperature between  $0^{\circ}$  and  $100^{\circ}$  C., it was found that hydrogen penetrated to the oxide layer and accumulated between the sheets. The pressures of the gas were sufficient to cause a complete separation of the sheets at all points except at the edges, where they had been welded together. The degree of bulging could be made to be as much as  $\frac{1}{4}$  inch, but this of course was determined by the length of time the discs were kept in the acid, and by the rate of acid attack; the latter increasing with the acidity and the temperature. At temperatures approaching  $100^{\circ}$  C. complete separation of the sheets occurred in the course of a few minutes, but at low temperatures much longer times were required. It may be interesting to note that since this separation of the sheets could be brought about at  $0^{\circ}$  C., when there could be no possibility of the formation of steam or any material quantity of water vapour, Law's explanation does not seem to be tenable.

Purely qualitative experiments were made to ascertain whether the diffusion of hydrogen could be prevented, and pickling, that is, the cleaning of the surface of the sheet, still effected. By making one of the above-mentioned discs the anode, and any other metal the cathode, using dilute sulphuric acid as the electrolyte, and passing a current of a few amperes through the solution, it was found possible completely to dissolve these discs without showing signs of hydrogen diffusion at any stage.

Another experiment was made by taking a strip of one of these compound sheets and rolling it down to a very thin gauge, with intermittent annealing. One-half of this was then pickled in the usual manner, but at ordinary temperatures, and the other half electrolytically pickled (Fig. 7, Plate III.). It will be seen that the portion which was electrolytically pickled is perfectly smooth and shows no signs of blisters, whilst there are clear indications of blisters on the other part.

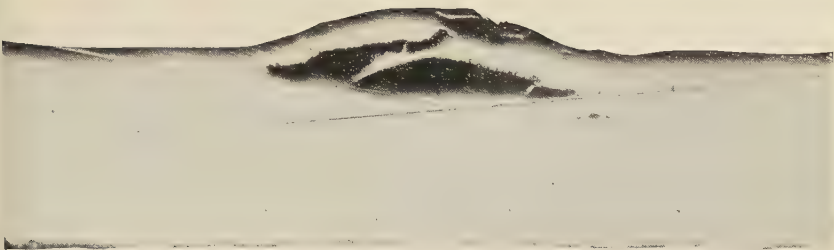


FIG. 1.



FIG. 2.

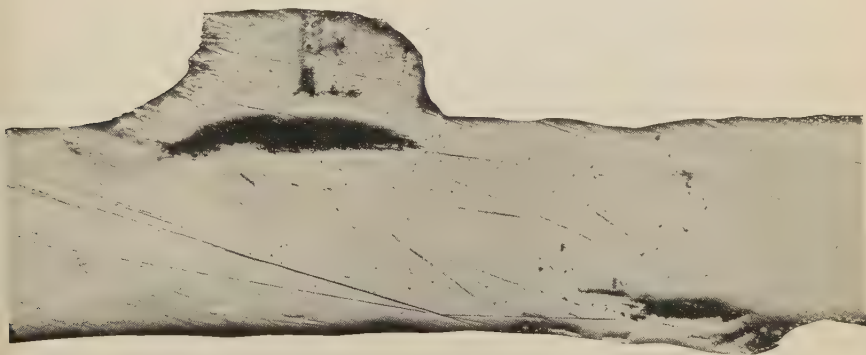


FIG. 3.



FIG. 4.

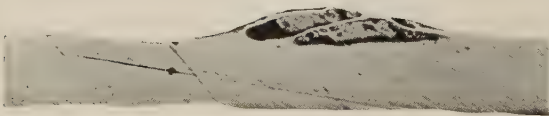
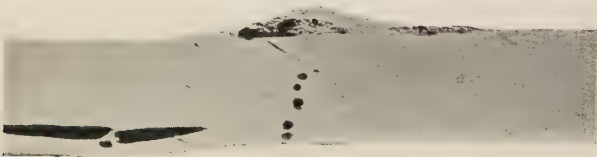


FIG. 5.





FIG. 6.

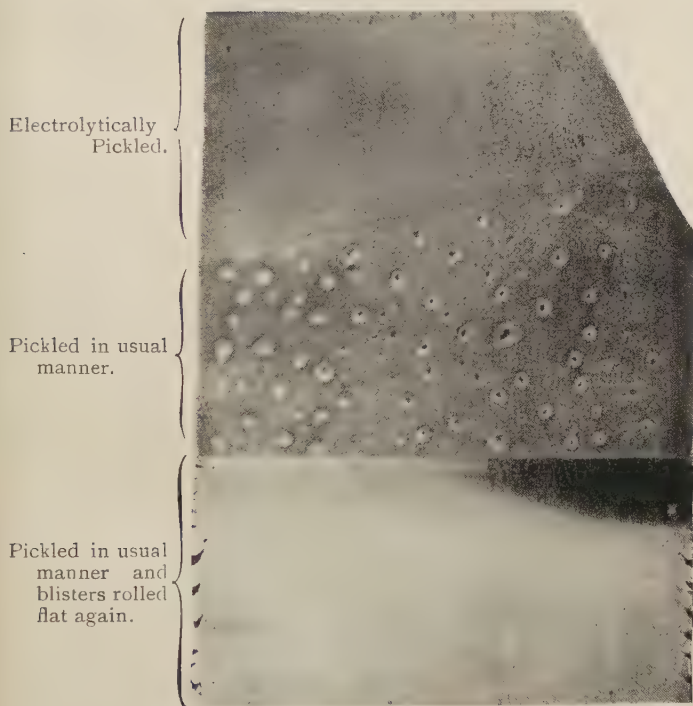


FIG. 7.



Attempts were made to replace the oxide film by one of carbide of iron, but, so far, these have not been successful. It is, therefore, impossible to say with any degree of finality that this constituent, or manganese sulphide, will, or will not, behave like oxide inclusions, but the author is very much inclined to believe it will. In this connection it is of interest to note that by covering a perfectly clean plate with a film of collodion, on one side only, and immersing the sheet in dilute sulphuric acid, blisters are produced under the collodion. These do not persist for long, however, presumably because the hydrogen diffuses through the collodion. Another interesting demonstration of a similar kind was obtained by taking an enamelled dish from which some of the enamel had been removed from the inside; after allowing cold dilute sulphuric acid to rest in this dish for some time, it was found that considerable quantities of the enamel became flaked off the outside surface. In this instance it was found that the pattern obtained by the flaking off of the enamel corresponded with that of the acid attack on the inside of the dish.

#### QUANTITATIVE MEASUREMENTS.

After having reached this stage in the investigation the author thought it would prove useful, as a further step in the study of pickling, and certainly interesting from a purely theoretical point of view, to make a careful examination of the conditions which govern the rate of hydrogen diffusion through steel. Quantitative evidence in this direction seems essential before going further with the more important aspects of the practical problem, such as endeavouring to devise a commercial method of preventing, or even regulating, the degree of hydrogen diffusion into steel during pickling. Many different kinds of apparatus were made, and tried, before any real success was achieved. In view of the possibility of a large number of tests being required, it was considered desirable to use the simplest form of apparatus consistent with a reasonable degree of accuracy.

A sketch of the apparatus finally decided upon is shown in Fig. 9. A is a stout glass cylinder with a carefully ground flange at the bottom; B represents the sample of sheet steel under examination; C is what may be described as a strong glass saucer with a

substantial flange, the upper surface of which is ground like that on the cylinder A. Into the base of the saucer is fused a length of strong glass capillary tubing, bent as shown in the illustration. A perfect gas-tight fit was obtained by the use of two thick rubber washers well smeared with vaseline, and four strong metal clamps, only two of which are shown in the sketch. All air in the space below the experimental sheet was carefully excluded before each test was made, by pouring mercury through the glass capillary. This was done after the sheet was in position, but before the clamps

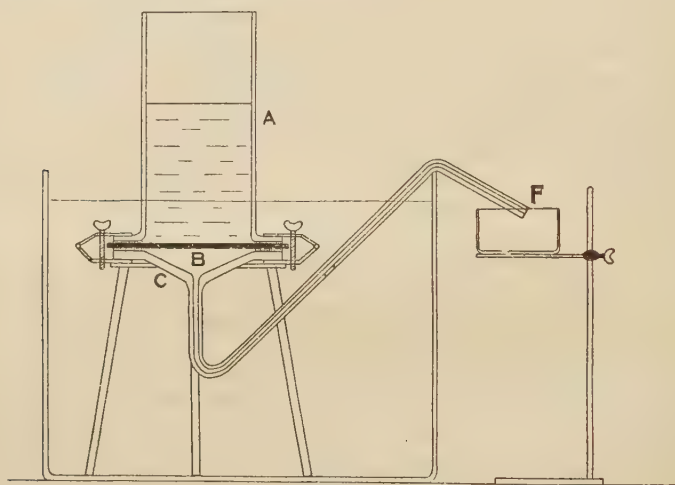


FIG. 9.

were screwed down, the last trace of air being removed by tilting the apparatus whilst a good stream of mercury was flowing between the sheet and the lower rubber washer. The pressure of mercury causing this flow was maintained whilst the clamps were being screwed down as far as they would go. This apparatus rested in a retort stand and could be immersed in a bucket of water ; under these conditions it was possible to conduct experiments at a desired constant temperature anywhere between  $0^{\circ}$  and  $100^{\circ}$  C. Before starting an experiment sufficient time was allowed for the apparatus to reach the desired temperature, the measured quantity of acid being separately heated to the same temperature. The acid was poured into the glass cylinder A, and was thus brought into contact with the upper surface of the sheet, with the generation



of hydrogen. Any hydrogen which diffused through the metal displaced a corresponding volume of mercury, forcing it out of the capillary tubing at F, where it could be collected and weighed at convenient intervals of time. By weighing the mercury more accurate determinations of the volume of hydrogen diffused were obtained than could have been attained by any convenient method of measuring the volume directly.

The circular portion of the sheet which was in contact with the acid was 2.5 inches in diameter, corresponding with an area of 31.67 centimetres.

During the earlier experiments that were made it became evident that, although the apparatus was capable of giving the required degree of accuracy, there was a possible disturbing factor in the specimens themselves which must be kept constant if comparative results were to be obtained. For example, it was noticed that different results were obtained if the surface of the sheet in contact with the acid had, or had not, a coating of oxide upon it. This was the case even when every care was taken to keep all other disturbing factors constant. In view of this, special care was taken in selecting sheets to see that all had, as nearly as could be estimated from a visual examination, about the same amount of oxide of iron upon them. To still further guard against irregularities arising from this cause, each complete set of tests was made with samples that were cut from the same sheet, and care was taken to ensure that the acid attack was always on the same side of the specimen in relation to the original sheet from which they were cut.

All experiments have been made with hot-rolled sheets, or, in the case of thick specimens, with samples that had been heated to and cooled from 900° C. In all cases, unless otherwise stated, the volume of solution employed was 100 cubic centimetres.

#### EFFECT OF VARYING $\text{H}_2\text{SO}_4$ ACIDITY ON THE RATE OF HYDROGEN DIFFUSION.

*Hot-Rolled Sheets 0.005 Inch Thick.*—In this series of experiments a wide range of solutions of sulphuric acid in water was used. The temperature was the same in each case, namely, 18° C. The results are given in Tables I. to VIII. The volumes of hydrogen diffused have been corrected for 0° C.

From the nature of the subject under consideration, it will be readily understood that the results could be examined from two different points of view. It would be possible (a) to estimate the volume of hydrogen diffused during a period of time which could be kept the same in each case, or (b) to determine the time required for the diffusion of a constant volume of hydrogen. So far as the author can see, neither method possesses any definite advantage over the other. In both there would be a factor which changes with variations in the strength of acid used, namely, the amount of iron dissolved. For the purpose of the present investigation it was decided to estimate the times required for the diffusion of 4 cubic centimetres of hydrogen. These times were obtained after plotting the results which are given in the tables, and reading off the values corresponding with the above-mentioned volume. These values have been plotted graphically against the respective acidities of the solutions used (see Fig. 10, p. 23). From this curve it will be observed that the rate of diffusion rapidly increases as the acidity is raised from about 5 per cent. to 15 per cent., and very slowly as the acidity is further increased.

TABLE I.—4.9 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	25	0.129
3	25	1.060
17	55	15.350

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 8 hours.

TABLE II.—9.8 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
2	20	0.63
4	20	2.10
5	5	2.71
6	15	3.70
12	20	10.69

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 6 hours 36 minutes.

TABLE III.—37·0 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	0	0·43
2	0	1·39
3	0	3·05
4	8	5·28
5	0	7·28
6	0	9·62
7	0	12·11

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 3 hours 30 minutes.

TABLE IIIA.—108 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ 

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	30	2·02
2	45	5·52
3	22	7·78
3	45	9·04
4	20	12·05

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 2 hours 12 minutes.

TABLE IV.—184 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
2	0	4·47
3	0	9·52
3	30	12·47

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 48 minutes.

TABLE V.—282 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	0	1·57
2	0	6·18
2	30	9·39
3	0	13·57

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 30 minutes.

TABLE VI.—381 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	0	1.81
1	30	4.41
2	0	7.41
2	30	11.35
2	40	12.66

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 24 minutes.

TABLE VII.—571.5 Grammes  $H_2SO_4$  per Litre. Temperature,  $18^\circ C$ .

Duration of Test.		Volume of Hydrogen, at $0^\circ C$ , Diffused.
Hours.	Minutes.	C.c.
1	30	5.89
1	47	7.93
2	5	10.19
2	20	12.19

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 6 minutes.

TABLE VIII.—762 Grammes  $H_2SO_4$  per Litre.

In this case there were 2.75 cubic centimetres of hydrogen diffused at the end of 1 hour 15 minutes, but the rate of acid attack had sensibly decreased before that time, and afterwards ceased altogether.

There was no perceptible action with another test in which 950 grammes of sulphuric acid were present per litre.

The expression for the curve in Fig. 10 is :

$$y = \frac{C}{x^{0.4167}}$$

where  $y$  = the time in hours for the diffusion of 4 cubic centimetres of hydrogen ;

$x$  = the acidity in grammes per litre of  $H_2SO_4$  ;

and  $C$  = a constant which for the curve in question is 15.55.

It may be of interest to note that curves of the same type are obtained by plotting the times required for the diffusion of any particular volume of hydrogen against acidity. The only difference



in the above expression for the various curves obtained in this

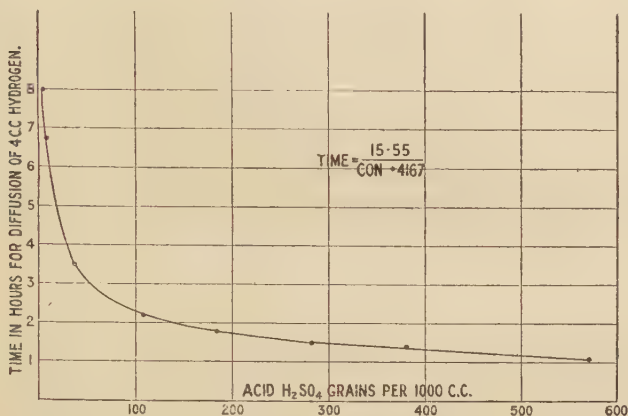


FIG. 10.

way is that the value of the constant  $C$  changes. These changes in the value of  $C$  can be found from the following equation :

$$y = x^{0.5688} \times 6.998 + 0.00127x^3.$$

#### INFLUENCE OF VARYING TEMPERATURES ON THE RATE OF DIFFUSION WHEN USING NORMAL $H_2SO_4$ SOLUTION, 4.9 GRAMMES PER LITRE.

The same kind of sheets were used for this series of tests as for those just described. The results are given in Tables IX. to XIV., and the estimated times for the diffusion of 4 cubic centimetres of hydrogen are plotted against the corresponding temperatures in Fig. 11. It will be observed that the points lie very close to a perfectly smooth curve, the expression for which is :

$$y = \frac{30}{x} + 0.004x$$

where  $y$  = the time in hours,  
and  $x$  = the temperature.

That is, the time required for the diffusion of a given volume of hydrogen is practically inversely proportional to the temperature.

In considering these results as they stand, it is of some importance to remember that the curve does not simply represent the diffusibility of hydrogen through the steel at different

temperatures. There is clearly another variable included which must have a substantial influence upon the results. For example, the rate at which the metal dissolves must increase rapidly with the temperature, and, therefore, the quantity of hydrogen generated per unit of time must also vary to the same extent. There is every reason to suppose that the rate of hydrogen diffusion is not only governed by temperature itself, but also by the rate at which the hydrogen is generated upon the surface of the metal upon

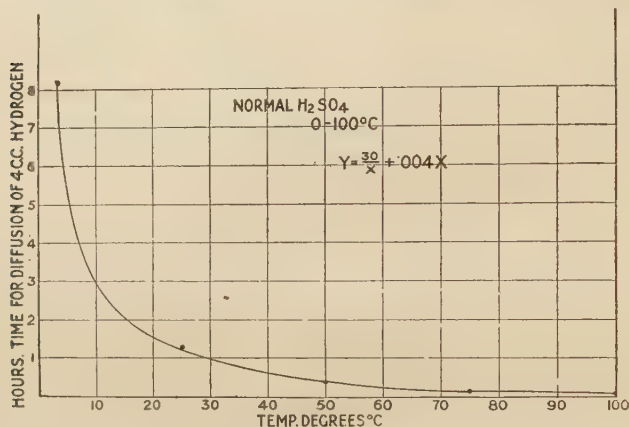


FIG. 11.

which the acid is acting. It was not possible, in this series of experiments, to make a reliable separation of these two variables, but a special attempt was made later with this object in view.

#### SERIES OF TESTS USING NORMAL SULPHURIC ACID AT VARYING TEMPERATURES.

TABLE IX.—*Temperature, 3.5° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	C.c.
3	0	0.52
5	0	1.55
7	0	3.06
9	30	5.08

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 8 hours 12 minutes.

TABLE X.—*Temperature, 12° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	C.c.
0	30	0·165
1	15	1·05
1	45	2·14
2	25	4·03
2	45	5·09

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 2 hours 24 minutes.

TABLE XI.—*Temperature, 25° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	C.c.
0	45	1·32
1	0	2·42
1	15	3·68
1	30	5·14

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 19 minutes.

TABLE XII.—*Temperature, 50° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	C.c.
0	15	1·58
0	20	2·75
0	25	4·19
0	30	5·65

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 24 minutes.

TABLE XIII.—*Temperature, 75° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	C.c.
0	5	1·20
0	8	2·87
0	10	4·09
0	12	5·11

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 9·5 minutes.

TABLE XIV.—*Temperature, 100° C.*

Duration of Test.		Volume of Hydrogen, at 0° C., Diffused.
Hours.	Minutes.	
0	3	1.135
0	4	2.35
0	5	3.15
0	6	3.89
0	7	4.41

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 6.1 minutes.

### EXPERIMENTS WITH HYDROCHLORIC AND SULPHURIC ACIDS OF VARYING STRENGTHS AT 50° C.

The same kind of sheets were used for these series as for those previously described. The results obtained with hydrochloric acid solutions are given in Tables XV. to XXII., and those with sulphuric acid solutions in Tables XXIII. to XXX. For

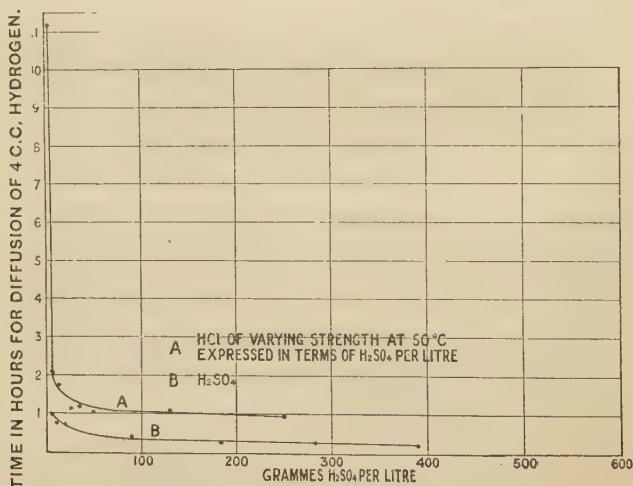


FIG. 12.

the purpose of comparison, the estimated times for the diffusion of 4 cubic centimetres of hydrogen for both series have been plotted on the same chart, Fig. 12. The acidities for the hydrochloric acid solutions have been calculated to, and plotted in, terms of grammes H<sub>2</sub>SO<sub>4</sub> per litre. From a glance at these

curves, it will be noticed that the rate of diffusion is considerably quicker when sulphuric acid solutions are used than when hydrochloric acid solutions of corresponding acidities are employed. Here again, however, it is necessary to state that no account is taken in these curves of any difference in the rate at which the iron may be dissolved by the two kinds of solutions.

SERIES OF TESTS WITH SHEETS 0·005 INCH THICK, USING  
HYDROCHLORIC ACID SOLUTIONS AT 50° C.

TABLE XV.—1·94 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
1	0	0·046
2	0	0·17
3	30	0·46
4	50	0·76
8	40	2·40

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 11 hours 12 minutes.

TABLE XVI.—3·87 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
1	5	1·26
1	30	2·50
2	30	5·55

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 2 hours 6 minutes.

TABLE XVII.—9·32 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·203
1	0	1·09
1	30	2·67
1	45	3·76

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 47 minutes.



TABLE XVIII.—18·64 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·64
1	15	5·21

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 8 minutes.

TABLE XIX.—25·8 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·44
0	45	1·23
1	0	2·57
1	15	4·18
1	45	7·25
2	15	10·47

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 13 minutes.

TABLE XX.—36·5 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·60
0	45	1·73
1	0	3·21
1	15	6·80
1	30	8·74

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 4 minutes.

TABLE XXI.—97·1 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·48
0	45	1·28
1	0	2·69
1	15	4·79
1	30	7·27
1	45	10·00

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 10 minutes.

TABLE XXII.—185·8 Grammes *HCl* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	1·09
0	45	2·84
0	50	3·32

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 54 minutes.

# SERIES OF TESTS WITH SHEETS 0·005 INCH THICK, USING SULPHURIC ACID SOLUTIONS AT 50° C.

TABLE XXIII.—4·88 Grammes *H<sub>2</sub>SO<sub>4</sub>* per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·90
0	45	2·58
0	55	3·70
1	0	4·25
1	10	5·38

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 57 minutes.

TABLE XXIV.—9.76 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	15	0.14
0	50	5.56

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 45 minutes.

TABLE XXV.—18.5 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	10	0.07
0	20	0.78
0	30	2.05
0	40	3.50
0	50	5.23
1	0	7.15

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 43 minutes.

TABLE XXVI.—37.0 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	10	0.20
0	26	3.05
0	31	4.22
0	37	5.54
0	45	7.25

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 30 minutes.

TABLE XXVII.—90.6 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	10	0.49
0	20	2.59
0	30	5.71
0	40	8.98

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 25 minutes.

TABLE XXVIII.—184·0 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	5	0·26
0	10	1·23
0	15	2·75
0	20	4·58
0	25	6·51

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 18·5 minutes.

TABLE XXIX.—282·0 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	5	0·28
0	10	1·52
0	15	3·80
0	20	6·46
0	25	9·27

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 15·5 minutes.

TABLE XXX.—381·0 Grammes  $H_2SO_4$  per Litre.

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	5	0·85
0	10	2·97
0	15	5·80

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 12 minutes.

#### NORMAL HYDROCHLORIC ACID AT TEMPERATURES BETWEEN 0° AND 100° C. SHEETS 0·005 INCH THICK.

The detailed results for this series are given in Tables XXXI. to XXXVII., and the times taken for the diffusion of 4 cubic centimetres of hydrogen are plotted against temperature in

Fig. 13. The points lie very close to a smooth curve, which may be approximately expressed as follows :

$$y = \frac{100}{x} + 0.009x$$

where  $y$  = the time in hours,

and  $x$  = the temperature in degrees centigrade.

It is interesting to note that on comparing the results of this series of experiments with those obtained with normal sulphuric

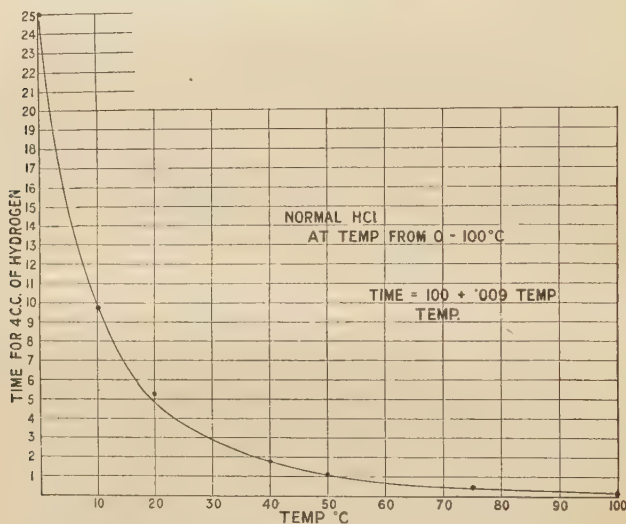


FIG. 13.

acid at corresponding temperatures (see Fig. 10), there is a similar difference in the rate of diffusion, as was observed for the two series of experiments that were made at 50° C., when using HCl and H<sub>2</sub>SO<sub>4</sub> solutions of varying acidities (see Fig. 12). Thus it would seem that the rate at which hydrogen will diffuse through steel is greater when the gas is generated, on the surface of the metal, from sulphuric acid solutions than from solutions of hydrochloric acid. This rather interesting observation holds good for all temperatures and acidities. This seems to be a remarkable fact, for it is scarcely in the direction that would have been anticipated. At first it was thought that it might be due to the presence of traces of free chlorine in the hydrochloric acid solutions acting as an oxidising agent on some of the hydrogen



NORMAL HYDROCHLORIC ACID AT TEMPERATURES BETWEEN  
0° AND 100° C.TABLE XXXI.—*Temperature, 0° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
16	0	1·46
18	0	1·91
21	0	2·64
23	0	3·26
26	0	4·43

Estimated time for the diffusion of 4 cubic centimetres of  
hydrogen, 25 hours.

TABLE XXXII.—*Temperature, 10° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
5	15	1·71
16	20	8·57
17	45	9·47

Estimated time for the diffusion of 4 cubic centimetres of  
hydrogen, 9 hours 45 minutes.

TABLE XXXIII.—*Temperature, 20° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
3	0	1·21
4	30	2·91
5	30	4·22
6	30	5·89

Estimated time for the diffusion of 4 cubic centimetres of  
hydrogen, 5 hours 20 minutes.

TABLE XXXIV.—*Temperature, 40° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	45	0·898
1	15	1·62
1	30	2·62
1	45	3·81

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 48 minutes.

TABLE XXXV.—*Temperature, 50° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	30	0·60
0	45	1·73
1	0	3·21
1	15	6·80
1	30	8·74

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 1 hour 4 minutes.

TABLE XXXVI.—*Temperature, 75° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	10	0·56
0	20	2·35
0	30	5·13
0	37	7·22

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 26 minutes.

TABLE XXXVII.—*Temperature, 100° C.*

Duration of Test.		Volume of Hydrogen Diffused, Calculated to 0° C.
Hours.	Minutes.	C.c.
0	5	1·74
0	7	3·27
0	9	4·69
0	11	6·01
0	13	7·11
0	15	8·17

Estimated time for the diffusion of 4 cubic centimetres of hydrogen, 8 minutes.

at the moment of its liberation on the surface of the metal, but it must be admitted that there were no real reasons for suspecting free chlorine could be present. In order to eliminate the possibility of free chlorine being present, and with the object of getting more light on this side of the question, some further experiments were made. It was thought that free chlorine could be guarded against, and still get a more clear idea of the cause of the differences just noted, by not using hydrochloric acid at all. For example, if the decreased rate of diffusion when using hydrochloric acid solutions was due simply to the presence of chlorine ions in solution, then some indication of this should be obtained by introducing sodium chloride to a solution of pure sulphuric acid in water. To test this, some of the same sheets as previously employed were taken, and examined in the usual manner; in the first case 100 cubic centimetres of pure sulphuric acid solution, containing 108 grammes  $H_2SO_4$  per litre, was used; in the second test a similar quantity of the same acid was used, but to this was added 1 gramme of sodium chloride; and in the third case the same amount of acid was used, but in this instance 5 grammes of sodium chloride were added. The results are given in the following tables:

TABLE XXXVIII.—*Pure Sulphuric Acid Solution containing 108 Grammes  $H_2SO_4$  per Litre. Temperature, 18° C.*

Time.		Volume of Hydrogen Diffused.
Hours.	Minutes.	C.c.
0	30	4·08
0	50	8·99

TABLE XXXIX.—*Same Solution as above, with 1 Gramme of Sodium Chloride added to 100 c.c. Temperature, 18° C.*

Time.		Volume of Hydrogen Diffused.
Hours.	Minutes.	C.c.
1	0	4.0
1	15	6.88
1	30	10.32

TABLE XL.—*Similar Solution to which 5 Grammes of Sodium Chloride had been added to 100 c.c. Temperature, 18° C.*

Time.		Volume of Hydrogen Diffused.
Hours.	Minutes.	C.c.
1	0	2.09
1	15	4.21
1	30	6.49
1	45	11.38

From the above results it is quite clear that the presence of sodium chloride in solution definitely decreases the rate of hydrogen diffusion. The author is not prepared to suggest how this is brought about, but intends to carry out experiments with this in view.

#### THE INFLUENCE OF THE THICKNESS OF METAL ON THE RATE OF DIFFUSION.

At this stage it may be useful to consider a series of experiments that were made with the object of determining the influence of varying the thickness of the metal upon the rate of diffusion. As it was desired to make tests with a wide range of thicknesses, it was important to standardise the conditions, so as to ensure getting comparative data. Accordingly, it was decided to use the same temperature in each case, and determine the volume of hydrogen that diffused through the metal in a given time. By adopting a standard time and the same temperature and acidity, it could be assumed that the rate at which the iron was dissolved, and therefore the hydrogen liberated, was the same in all cases. All the samples were very low carbon steels, but they were not

from the same cast, and consequently there were, no doubt, slight differences in their chemical composition. It was thought, however, that these differences would not be sufficient to have a serious effect upon the results.

Since it was impossible, at the outset, to decide what would be the most suitable period over which to carry the tests, intermittent observation of the volume of hydrogen diffused were made, and graphs were plotted from these data. From these curves the volume of hydrogen diffused for any particular time

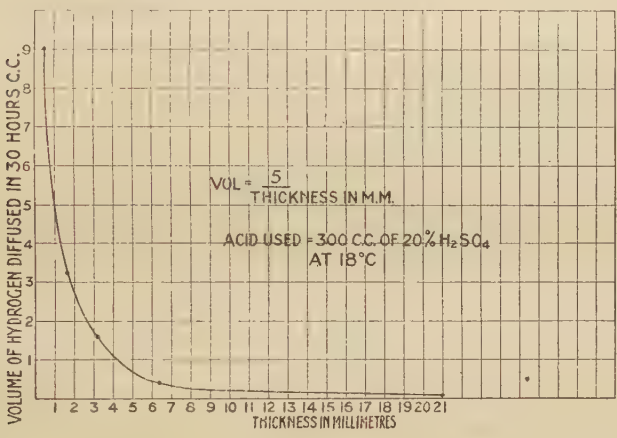


FIG. 14.

could be estimated. A period of thirty hours was ultimately chosen. The results are recorded in the following table, and plotted in Fig. 14. In each experiment 300 cubic centimetres of solution containing 20 per cent. H<sub>2</sub>SO<sub>4</sub> was used.

TABLE XLI.

Thickness of Metal.	Volume of Hydrogen after Thirty Hours.
Mm.	C.c.
0.483	9.0
1.588	3.16
3.175	1.60
6.35	0.52
20.45	0.059



The values obtained lie on a very smooth curve, which can be approximately expressed as follows :

$$y = \frac{5}{x}$$

where  $y$  is the volume in cubic centimetres, and  $x$  the thickness of the steel in millimetres, or the volume of hydrogen diffused is, for all practical purposes, inversely proportional to the thickness of the metal.

#### SURFACE OXIDE ON THE SHEET.

Earlier in the paper it was stated that there were reasons for believing the rate of hydrogen diffusion through steel was affected by the presence of a coating of oxide on the surface of the metal. During the early stages of the investigation it was not possible to make anything in the nature of quantitative tests in this direction, and to avoid any irregularities being introduced into the results from this cause, special care was taken to ensure that the character of the surface was the same. Later, however, it became possible to make some experiments with this variable in mind. To do this, outside sheets from hot-rolled bundles of 0·005 inch thick sheets were selected. Naturally, the outer surfaces of such sheets were covered with a compact layer of black oxide of iron. When a bundle of sheets is sheared and opened the film of oxide, between each, almost invariably adheres to one sheet, leaving the other absolutely clean, and showing a bright metallic surface. Knowing this, it was possible to get outside sheets from which the oxide had been entirely removed from the inner surface by its sticking to the neighbouring sheet.

All the results obtained were so similar that it is only necessary to give those from one pair of tests. In both, the sample was cut from the same sheet, but in one it was placed in the apparatus in such a way as to have the acid attacking the clean surface, whilst in the other the oxide surface was attacked. The results are given below :

*Sheet with the Oxide Surface in Contact with the Acid.*

Time.		Volume of Hydrogen Diffused.
Hours.	Minutes.	
1	20	C.c. 1·53
2	0	3·31
2	15	4·09

*Sheet with Clean Surface in Contact with the Acid.*

Time.		Volume of Hydrogen Diffused.
Hours.	Minutes.	C.c.
1	20	1.20
2	0	2.51
2	15	3.07

From the above figures it will be seen that the passage of hydrogen through the metal is substantially quicker when the oxidised surface is acted upon. The author is not at present able to give a definite explanation of these facts. There are no doubt numerous ways of explaining them, amongst which may be mentioned: (a) The surface of the metal below the oxide coating may be more irregular than an inside surface, which would mean that the surface area in contact with the acid would be larger in the former than in the latter. (b) The presence of undissolved oxide of iron might set up a galvanic action, and thus cause the iron to go into solution more rapidly than if no oxide were present. (c) The presence of oxide might cause the hydrogen to be liberated in more intimate contact with the metal, and thus allow more opportunity for the gas to enter and pass through the sample.

#### INFLUENCE OF TEMPERATURE ON THE RATE OF SOLUTION OF IRON.

At this stage it was decided to make careful observations of the effect of temperature on the rate at which iron is dissolved in acid solutions, and at the same time correlate these with the diffusibility of hydrogen. In this way it was hoped to obtain useful data, from a practical point of view, which would form the base line from which to commence a study of possible means of preventing, or at least controlling, this diffusion. For this purpose it was necessary to start with sheets with one surface quite free from oxide. By having this surface in contact with the acid it was possible to make accurate determinations of the amount of iron dissolved during each test, then calculate the amount of hydrogen generated, and thus judge the amount of hydrogen diffused in relation to the quantity generated. Even when these precautions are taken, it must be confessed that there is still another variable factor which is not accounted for. For

example, by adopting a standard time, which in the present instance was ten minutes, and varying the temperature, the quantity of iron dissolved varies, and consequently the thickness of the sheet changes during the test, but these changes are not of the same degree for different temperatures. From a practical point of view this, however, need not be considered, for precisely the same kind of variations prevail in ordinary pickling.

The important results are recorded in Table XLII. and plotted in Fig. 15. From curve *a*, which represents the amount

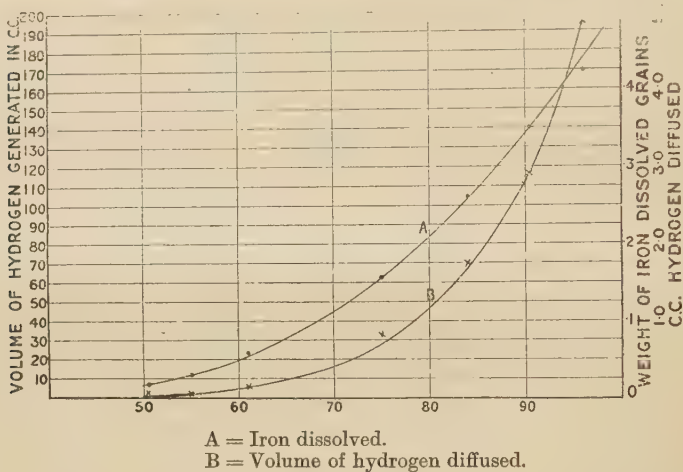


FIG. 15.

of iron dissolved at the different temperatures, it will be seen that this increases with the temperature. The same curve with different values for the vertical ordinates also represents the rate at which hydrogen is liberated. In the case of iron the curve can be expressed in the following form :

$$\text{Iron} \times 10^{10} = \frac{x^5}{2} + 0.0014 (x - 48).$$

The curve *b*, for the volume of hydrogen diffused through the steel, is :

$$\text{Volume in cubic centimetres} \times 10^{14} = \frac{x^{7.75}}{5}$$

In both cases, *x* corresponds with the temperature.

This series of experiments not only quite clearly show the effect of temperature on the rate at which the iron is dissolved, and the rate hydrogen is diffused, but they can be used for the purpose of calculating the percentage of hydrogen which passes through the metal. This has been done, and the figures are given in the last column of Table XLII., where it will be noted that the

TABLE XLII.

Temperature Deg. C.	Volume of Hydrogen Diffused.	Weight of Iron Dissolved.	Hydrogen Equivalent of Iron.	Percentage Hydrogen Diffused.
	C.c.	Grm.	C.c.	
96·0	4·87	0·426	170·0	2·87
90·5	2·90	0·352	139·8	2·07
84·0	1·74	0·262	104·1	1·67
75·0	0·844	0·158	62·9	1·34
61·0	0·147	0·0588	23·4	0·625
55·0	0·067	0·0294	11·68	0·577
50·5	0·088	0·0182	7·23	1·23

percentage of hydrogen that diffuses steadily decreases with the temperature down to, say, 55° C., when it is only one-fifth of the percentage which goes through at 96°.

A number of miscellaneous experiments have been made with the object of making a general survey of the influence of the addition of colloids to the acid, upon the rate of solution of the iron, and the diffusion of hydrogen. Others have been made with additions of different oxidising reagents to the acid solutions, and it has been found possible to prevent the diffusion of hydrogen in this way. These preliminary observations are now being extended, and it is hoped to have the results ready for publication at an early date.

#### DIFFUSION OF HYDROGEN THROUGH A SINGLE CRYSTAL OF IRON.

Many investigators who have worked on the embrittling of iron by hydrogen have been inclined to the view that this embrittling is to a large extent due to a marked difference in the solubility of the gas in the amorphous cement, which is supposed to exist at the crystal boundaries, and the crystalline material

itself, see J. H. Andrew <sup>(11)</sup> and others. Indeed, it has been thought that the gas is only soluble to a very limited extent in the crystalline phase. Whether this be the case or not the author is unable to say ; but if it be, he would be inclined to expect that the rate of diffusion of the gas would be affected to an appreciable degree by any large variation in the size of the crystals within the metal. In order to test whether this was the case, the author took one of the specimens recently made by Mr. Pfeil and himself, <sup>(12)</sup> which contained a crystal  $1\frac{1}{2}$  inch diameter and going right through the strip of  $\frac{1}{16}$  inch thick. Another portion of the same specimen was refined by heating to above the A3 change, and thus made finely crystalline. Both pieces were tested in a special small apparatus like that illustrated in Fig. 9, and each experiment was made with acid of the same strength and at the same temperature. It was found that the hydrogen passed through the single crystal, and no difference in the rate of diffusion could be detected in the two experiments.

#### GENERAL SUMMARY.

From the experiments described in the present paper the general conclusions that can be drawn may be briefly summarised as follows :

1. Caillietet's discovery that hydrogen which is being developed by acid attack upon iron and steel can enter and pass through the metal has been confirmed.

2. The presence of an inclusion such as oxide of iron will cause the hydrogen, which enters the metal in the atomic state, to be liberated at and around the inclusion in the molecular condition. The amount of hydrogen which accumulates at such inclusions is a function of the duration of pickling, the distance of the inclusion from the surface that is being acted upon by the acid, the strength of the acid used, and the temperature ; it increases with the time, temperature, and acidity, but is inversely proportional with the distance. It is believed that other impurities and constituents, such as sulphide of manganese and carbide of iron, behave in the same way as oxide of iron, but it has not yet been found possible to make reliable experiments whereby this view could be definitely tested. It has, however,



been shown that collodion and enamel will cause the liberation of hydrogen which has entered iron during pickling.

3. A simple apparatus has been devised with which it has been possible to make quantitative measurements of the rate at which hydrogen diffuses through iron and steel under varying conditions of acidity and temperature.

- (a) The influence of acidity, when using sulphuric and hydrochloric acids in water, upon the rate of hydrogen diffusion has been determined.
- (b) The rates of hydrogen diffusion, when using normal solutions of sulphuric acid, between  $0^{\circ}$  and  $100^{\circ}$  C., have also been determined.
- (c) The effects of temperature, when using normal sulphuric acid, on the rate of solution of iron have been examined, and these have been correlated with the rates of hydrogen diffusion.
- (d) It has been found that, other things being equal, the rate at which hydrogen diffuses through mild steel is inversely proportional to the thickness of the metal.

4. When dealing with thin sheets of steel it has been found that the presence or absence of a film of oxide of iron upon the surface has a marked effect on the rate at which hydrogen passes through the metal.

5. Experiments have been made with specimens of metal containing only one crystal in the area acted upon by the acid, and it was found that the hydrogen passed through this quite readily. Indeed, no difference in the rate of diffusion could be detected under these conditions as compared with specimens containing the usual small crystals.

6. The diffusion of hydrogen can be prevented by electrolytic pickling and by using suitable oxidising reagents in the acid. A certain amount of work has been done in this direction, and it is now being systematically extended.

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### DISCUSSION.

Mr. J. H. WHITELEY (Saltburn), in opening the discussion, said there was one line of investigation in the very interesting research described by the author which he did not seem to have followed up, but which, he thought, ought to yield some important information. If hydrogen in the molecular state could collect at points within the metal in sufficient quantity to give rise to comparatively large blisters, it should be possible to find evidence in that direction by careful examination under the microscope at high magnification, because, to make room for itself, the hydrogen must effect a separation between the various particles and the ferrite, with the result that small cavities containing the gas would be formed. It might take some considerable amount of work to find those cavities, and probably a large number of sections would have to be examined; yet in that way one might get to know definitely whether it was silicate or carbide or some other substance that prevented the passing of the ionic hydrogen through the metal, as the author suggested. The author referred several times to the embrittling action of hydrogen, and in that connection he desired to refer to a case, which came under his notice a short time ago, of a mild steel plate 1 inch thick which had been sent out for the purpose of making some sort of an oil-press. When it left the works it had a tensile strength of about  $27\frac{1}{2}$  tons per square inch and an elongation of about 30 per cent. It came back, after a little while, in an extremely brittle condition; in fact, it could be broken with a sledge-hammer, and on testing it was then found to have a tensile strength of 40 tons per square inch and an elongation of 4 per cent. There was nothing to be seen under the microscope to account for that change; in fact, it was quite clear that the piece had not been heated above  $Al_1$ . Its original pearlitic structure was still present. He found further that by normalising the steel its original ductile condition could be completely restored. A tensile strength of  $27\frac{1}{2}$  tons and an elongation of 30 per cent. were again obtained. Now, it was plain, from the appearance of the surface, that the piece had been pickled and an attempt made to galvanise it. He was so interested in the specimen that he determined to ascertain its hydrogen content. In order to do so he cut cylinders weighing about 100 grammes, heated them in dry air at  $950^{\circ}C$ . for an hour or more, and weighed the water formed—that treatment, of course, restoring the ductility of the steel. Several tests were made, and in no instance did the amount of hydrogen liberated exceed 0.001 per cent. In order to make quite certain of getting all the hydrogen he then drilled the cylinders, and burned the drillings in oxygen, weighing the further amount of water formed. The total

from the two heatings then amounted to 0.004 per cent. Apparently there was a compound present containing hydrogen which had not decomposed in the first heating. He thought the members would agree that that was a very small amount of hydrogen to cause such marked brittleness, and he would suggest that possibly, under certain conditions, it was the passage of hydrogen through the metal rather than its presence in the metal which might account for the extreme brittleness that was sometimes produced.

Mr. E. F. LAW (London) believed he was right in saying that it was something like eighteen years since the subject of pickling had been discussed by members of the Institute, and they were therefore most grateful to the author for introducing a subject which was of very real importance to at any rate a section of the iron and steel industry. On a most conservative estimate (because it was impossible to get exact figures) there would be employed in the tinplate industry in South Wales alone at least 2500 tons of sulphuric acid per annum, and over 4000 tons of steel were dissolved. If the galvanising trade were also borne in mind it would be appreciated that the process was a very important one, and that any economies which could be effected would be very valuable to those industries. Personally, he did not think the author's theory of the formation of blisters would quite hold water. He understood that, according to the author's theory, the hydrogen penetrated the steel until it met with some obstruction, and then it began to accumulate in what was described as a molecular form and caused a blister. If that happened in the case of an oxide inclusion, it would surely happen with other inclusions—in fact, the author said, with regard to manganese sulphide, on p. 17: "It is, therefore, impossible to say with any degree of finality that this constituent (carbide of iron), or manganese sulphide, will, or will not, behave like oxide inclusions, but the author is very much inclined to believe it will." The fact remained that it did not. If it did, every tin plate manufactured would have blisters, because there was manganese sulphide in every plate. He hoped the author would be able to explain that point, because personally he admitted he found it rather incomprehensible. If the author went into the subject a little more fully, as he was certain he would, he thought he would come to the conclusion that the formation of peppery blisters was due to the reduction of oxide. It was many years ago since he (Mr. Law) had expressed that view, and he would gladly withdraw it if he heard any reason against it. Up to the present he was, however, unrepentant.

Mr. C. H. RIDSDALE (Middlesbrough) said the author had endeavoured to locate the type of material which acted as an obstacle to the passage of hydrogen, and also the conditions of time, temperature, acid, and so on, under which hydrogen diffused through steel, and had referred to some work that he (Mr. Ridsdale) did many years ago. He thought

the facts he then found still held good. In the first place, although he was not then very much concerned with the more theoretical side of the subject, he had formed the conclusion that the blistering was not necessarily due either to oxide or to any other material obstacle, but that it might in some cases be simply due to a microscopic porosity or lamination of the steel. He said "microscopic," because in one of the papers he wrote he gave the size which a porosity, such as might produce a pepper blister, would have to be, namely, 0.0000076 square inch area, equal to  $\frac{1}{360}$ th of an inch diameter.<sup>1</sup> It could not be called a blowhole. He did not have the opportunity then of going into the subject in the systematic way in which the author had done, because he was concerned only with the commercial point of view, and all his experiments were conducted in works under practical working conditions. The temperatures of the acid used were something like 185° to 200° F., and the strength of the acid (which was generally sulphuric) was one part of acid to three parts of water, except in the case of white pickling, in which it was rather weaker. One of the foremen at the works had first demonstrated to him one cause that produced blisters. He told his foreman that he felt certain that pickling for too long a time would produce blisters—a statement which the foreman confirmed, saying that if some plates that were first properly pickled were put back into the pickling bath for a few extra minutes, pepper blisters would be produced. That was proved by actual experiment. Finally, he experimented with a dozen plates produced under various conditions; each sheet was first perfectly pickled, then one-half was dropped into the bath and pickled longer. On this half pepper blisters were raised, there being a distinct line of demarcation between the good part and that with fine pepper blisters on it. The question then arose, "What were the conditions of manufacture which facilitated such a result?" and his attention was very soon directed to the question of oxidation, heating for too long a time, and overheating. One of the experiments tried was overheating the bars for various times—for instance, the unit time, the normal unit and a quarter, the unit and three-quarters, and twice as long. Pieces of the same bar were used in all the experiments. Finally, the tin-plates were sorted out at the various stages, and the percentage of blisters noted. Speaking broadly, it was found that the bars which had been heated too long always gave a larger proportion of pepper blisters. The same results were obtained if sheets by any means received more exposure to oxygen whilst hot, such as, for instance, the outside sheets of the pack to which the author referred, and slightly aired sheets out of annealing boxes. To sum the whole question up, the conclusion to which he came was that, in ordinary working, steel had about as much as it could bear in the various forms of treatment it received, and the moment it was given a little more acid, a little

<sup>1</sup> "Diseases of Steel," *Journal of the Iron and Steel Institute*, 1903, No. II. p. 260.



more heat, or a little more of any of the treatments to which it was subjected, blisters were obtained. One of the most interesting points referred to by the author was the question of adding oxidising or other agents to the bath to prevent blistering. He did not know to what agents the author referred in that connection, as, for instance, whether he referred to a substance which was called "Picklelette," which undoubtedly reduced the quantity of metal attacked and the amount of hydrogen absorbed by the metal. Personally, he had used that substance for scientific work in which he desired to attack the scale or oxide in steel but not dissolve the metal, and not get large transmission of hydrogen, and in certain scientific work of that kind he found it very useful. He hoped on a future occasion he would have an opportunity of saying more on that subject, as he had found it useful in various investigations. He would like to know whether the author had tried that substance to reduce blisters, &c., in his experiments.

Dr. WALTER ROSENHAIN, F.R.S. (National Physical Laboratory), said he had read the paper with special interest, because it was a study of a subject which was decidedly obscure, and, although he was not altogether satisfied that the author had established his theory, it had led him to carry out some interesting experiments, which was more than could be said for some theories. There were only two points he desired to raise. The first related to the subject of diffusion, of what all the previous speakers had referred to as hydrogen. Strictly speaking, it ought to be called hydrogen ions; consequently, it was in a very different condition from ordinary hydrogen, which did not diffuse even through thin steel at the ordinary temperature. He did not think anyone was able to say at present exactly how the hydrogen ion found its way through the space lattice of the iron crystal; he was presuming that it did go through the body of the crystal. It was known that minute atoms could go through the space lattices of crystals, so that it was not altogether surprising that the hydrogen atom should do so in the present instance. The author had drawn what he (Dr. Rosenhain) thought was an ingenious diagram of a number of dots representing atoms, and a very large, apparently non-atomic but homogeneous enclosure, and suggested that all the hydrogen ions could do was to stop at such an obstacle and accumulate. Personally, he could not see it in that light; he could not help thinking that if the concentration of the hydrogen ions increased sufficiently they could quite easily escape along the lateral channels, even though they came towards the obstacle along the channels at right angles to it. What he thought might happen, if the reduction of oxide theory were excluded, was that there were certain particles present in the crystals or in the crystal boundaries which acted as nuclei, perhaps as catalytic agents, which facilitated the combination of the hydrogen ions into molecules, and those no longer diffused, but stayed there. Whether that was purely a

mechanical action, as the author suggested, or whether it was a chemical action due to the presence of oxide, yet remained to be established. The author's very ingenious experiment of using double sheets was very pretty, but he was afraid inconclusive, for the reason that one could not be sure that no air space existed anywhere between the doubled sheets. If there were an air space, the experiment would break down immediately. The same remark also applied in regard to interstices within an actual steel sheet. If there were cavities, no doubt they would fill up.

There was only one other point to which he wished to refer—namely, that blistering as the result of the diffusion of hydrogen was not confined by any means to steel. The phenomenon known as the gassing of copper was well known, and there the theory of reduction of oxide by penetrating hydrogen was pretty well established. In aluminium a very similar phenomenon occurred. In aluminium treated in certain ways a condition could be obtained in which the sheets could be rolled perfectly well, so that the metal was rather more ductile than usual, but on annealing it blistered in the manner described for tin plates. That was entirely a question of gas content. In that case there was certainly no reduction of oxide by hydrogen, and as far as that fact went, it was in favour of the author's theory.

Dr. W. H. HATFIELD (Sheffield) said the paper naturally divided itself into two parts, one being the explanation of the blisters, and the other some extremely valuable constructive scientific work in connection with the action of acids in the pickling process. He thought the author's experimental work would prove to be very valuable as time passed, and the thanks of the members were due to him for it. Turning to the question of blisters, Mr. Law had put forward one explanation, and the author had put forward another. Frankly, he could not agree with Mr. Law's explanation as it stood, for the reasons put forward by the author. But neither did the author's explanation appeal to him as very convincing, and he (Dr. Hatfield) therefore desired to suggest a further explanation. A proper understanding of the question of the pickling of steel was an extremely difficult matter. Personally, he had given a lot of time to the subject over a large number of years, and he felt even now that he did not know much about it. There were, however, from his point of view, two aspects of the subject which should not be lost sight of, one being the embrittling of steel by the action of acid, and the other the production of blisters. It was always difficult fairly to judge the degree of embrittling, because almost invariably a very thin sheet was being dealt with. That sheet was being attacked by acid, and those who actually tested such sheets on the testing machine after pickling did not invariably polish the surface of the test-piece and obtain a perfectly plane surface, thus eliminating the roughening action of the acid, which was sometimes

very considerable, and, under some circumstances, was concentrated, and so caused the steel to behave as a brittle substance when intrinsically it was not. Mr. Whiteley had referred to the very small percentage of hydrogen he had been able to discover in a very brittle steel, and that, he thought, confirmed what he (Dr. Hatfield) had said. Personally, he had quite an open mind in regard to the influence of a considerable proportion of hydrogen intrinsically in embrittling steel; he had no conviction at all upon the subject. The question of blisters being raised on steel was a very important commercial question. It was a serious difficulty in many works, and it was most gratifying to find that the author was tackling the subject so seriously. There was one very simple way of looking at the matter—namely, that when a sheet was rolled the structure of the material was laminated. It was quite easy to conceive that, in the locality of an oxidising slag inclusion, there was an imprisonment of gas under high pressure in the sheet in the vicinity of the inclusion. When that sheet was rolled a very thin layer of metal was produced, but a layer strong enough on the top of the inclusion still to imprison the gas. The steel was then put in acid, and a considerable thickness of the steel which was actually imprisoning the gas was dissolved away, so that a very strong “air vessel” was made into a very flimsy one. That might, at any rate, be a possible explanation of some of the blisters which were encountered, and it would be appreciated that that explanation neither called for the explanation which Mr. Law put forward, nor for the ingenious explanation put forward by the author. A very interesting phenomenon of a similar order which confirmed the point he had put forward was that if wrought iron were cemented very serious blisters were caused; and it might well be assumed that, owing to analogous action of that kind during a manufacturing operation, some cause was produced in the neighbourhood of the defect which did not produce an obvious blowhole, but which resulted in gas being present to a sufficient extent to produce the effect he had mentioned. It was extremely gratifying to himself to find that diffusion through a single crystal was so effective.

Engineer-Captain J. A. RICHARDS, R.N. (London), said he thought the author was carrying out a very valuable work for the steel trades which dealt with pickled material. The author had referred on p. 12 to “small” blisters, and no doubt the specimens he illustrated in the paper were very highly magnified. Personally, he had had a very large experience of pickled material, chiefly boiler tubes and tubes of different kinds. He remembered once going into a tinplate works in South Wales and seeing a number of plates coming through after pickling and annealing. Some of the plates contained peppery blisters and some did not. On inquiring from the manager of the works the reason for the peppery blisters, he was informed that it was thought

they were due to some inherent defect of the steel, as all the plates had had the same pickling and the same heat treatment. He had met both types of blisters in the interiors of cold-drawn tubes. He had seen so many million tubes in his time that it would be impossible not to have obtained some experience of blisters. The large type of blisters he always put down to blowholes which had not welded up during manufacture, or, if they had welded up, there were sulphide segregations in the blowholes which raised the blisters. The smaller or peppery types he had always ascribed to some defect in the steel, as in the case of the tinplates referred to. The blisters generally appeared in certain parts of the interiors of the tubes, but they were absent in other parts which had received exactly the same amount of pickling and the same heat treatment; they were generally much smaller than those shown on Fig. 8 of the paper, and not punctured at the top, but entire. He remembered that at the Admiralty on one occasion there was a case of peppery blisters in boiler tubes for a ship. A number of the tubes were cut up through their longitudinal axes and carefully examined. These blisters were so minute that they could not be seen with the naked eye after the tubes had been cut up. From a practical point of view they had disappeared. This was often the case when viewing through a bright tube. Apparent defects were then seen which quite disappeared when the tube was cut through its longitudinal axis, and the two halves examined. The tubes in question were fitted into the boiler, and behaved quite as satisfactorily on service as other tubes which had not those superficial marks. Taken altogether, the Admiralty material had been extraordinarily free from blisters in solid-drawn steel tubes. The worst blisters he had ever seen were in iron strips, or hoops, as they were called in Scotland, for welded tubes. Those blisters had formed on each side of the strip, and made almost perfect spheres  $1\frac{1}{2}$  inch to 2 inches in diameter. He had a transverse section cut from one of the strips through a blister, which he showed to a friend, who told him that apparently the manufacturer had invented a new form of tube-making. He really thought that was so. The blisters had been raised during annealing, and were probably due to scale which had been left before faggoting. Many cases of similar blisters had been seen in lap-welded iron tubes, no doubt due to the same reason. The question of the hardening effect due to pickling was very interesting to anyone intimately connected with steel tubes, because some specifications laid down that the tubes were to be electro-zincd by the users of the tubes after receipt, so that they had to be pickled to take the zinc. A case occurred in 1912 of some tubes failing in the mechanical tests at a boiler works. It was thought to be due to over-pickling before zincing, so he carried out some experiments on twelve  $1\frac{1}{2}$  in. outside diameter  $\times$  11 in. gauge (0.116 inch) thick cold-drawn tubes. The tubes were close annealed, and seven test-pieces cut from each tube—that is, each test-piece



consisted of a short length of tube 14 inches long. The mean of the results were as follows :

	Breaking Load in Tons per Square Inch.	Elongation per Cent. on 8 Inches.
Tubes as close annealed . . .	21·6	36·4
Pickled for 1 hour in 1 part HCl to 39 H <sub>2</sub> O . . .	21·5	36·2
Pickled for 2 hours in 1 part HCl to 39 H <sub>2</sub> O . . .	21·7	34·2
Pickled for 3 hours in 1 part HCl to 39 H <sub>2</sub> O . . .	21·7	31·2
Pickled for 4 hours in 1 part HCl to 39 H <sub>2</sub> O . . .	21·9	28·1
Pickled for 6 hours in 1 part HCl to 39 H <sub>2</sub> O . . .	21·9	26·6
Pickled for 8 hours in 1 part HCl to 39 H <sub>2</sub> O . . .	22·2	23·8

From practice at various boiler works, it appeared that the length of time in pickling was a greater determining factor on the increased hardness of the tube than the strength of the pickle, but the author's tests hardly bore that out. Personally, he was under the impression that the pickle had a greater hardening effect on alloy steels than on ordinary low-carbon steels, and he hoped the author would make some experiments from that point of view. The Admiralty had always found that annealing at a very low temperature would remove all the hardness caused by pickling. In conclusion, he desired to thank the author for the great service he had rendered to the members by carrying out his experiments.

Mr. C. E. STROMEYER (Manchester) said he had not had any experience of the blisters referred to by the author, but experience was occasionally obtained of tubes which had been put into boilers suddenly developing pitting to an extraordinary extent. He remembered many years ago that a boiler which he inspected in Glasgow started to pit through the tubes before the ship had got to the Channel on her maiden voyage, and when the ship arrived in Japan the whole of the tubes had to be renewed. He did not know whether that had anything to do with the present subject, but it looked very much like it. If the tubes were subject to peppery blisters, these would probably start the pitting actively. Very similar cases had occurred since then, although not quite of so serious a character. In future, he would certainly look at the tubes from Dr. Edwards' point of view, because he thought there was a relationship between the two subjects.

He (Mr. Stromeier) had not noticed anything that suggested



peppery blisters having been active on boiler plates, but he recently came across a very peculiar case of bulging. A Stirling boiler tube developed small bulges of about  $\frac{1}{4}$  inch diameter and  $\frac{1}{8}$  inch deep. They appeared in rows. The metal was not reduced in thickness—in fact, the bulges looked as if they had been punched with a die. Whether they were due to the metal or to the water, or perhaps to water-hammer, he did not know, and he further did not know whether those bulges were related to the subject under discussion. The phenomenon of peppery blisters occurred also in copper. He believed in that case the explanation which the author gave was the accepted one—namely, that such blisters occurred only in under-poled copper, which therefore contained microscopic particles of oxide. When the plates were exposed to gases containing hydrogen, the hydrogen penetrated the copper, and when it met the oxides was converted into steam, the steam being at a sufficiently high pressure to burst the copper.

The blistering of blister steel was caused by a similar action. Instead of hydrogen, carbon entered the steel, and, when it met the oxide, carbonic acid was produced.

The PRESIDENT (Sir William Ellis, G.B.E.), in proposing a cordial vote of thanks to the author for his excellent paper, which had been so well received and discussed, said he desired to ask a question with regard to Fig. 8 on Plate III. If it were the fact that the blisters shown in the section marked “pickled in usual manner” were the result of pickling and not of inherent defects in the steel, as he took it the author assumed, looking at the matter from a manufacturing point of view, why should those blisters be developed by using that method when, as shown on the first part of the plate, those defects were not developed, if the metal were electrolytically pickled? The answer to the question really stared the members in the face, but he would like the author to reply to it.

The resolution of thanks was then put and carried with acclamation.

Professor C. A. EDWARDS, in reply, said he had listened to Mr. Whiteley's observations with great pleasure. He thought, however, it would be an extremely difficult matter to detect microscopically the very minute extensions to which Mr. Whiteley referred. He did not think the amount of hydrogen Mr. Whiteley mentioned was in any way a small quantity when the facts of the matter were borne in mind. It was necessary to be very careful in attempting to measure the amount of hydrogen which was absorbed by steel as a result of pickling; otherwise there was a danger of obtaining variable results. In that connection he would draw attention to the fact that if a sample of steel were pickled and then put on one side with the intention of continuing the experiment later, the hydrogen, or part of it, that had been

absorbed during pickling would be coming out the whole time ; so that it was necessary to bear in mind the time factor. He was also very glad to have had the opportunity of listening to Mr. Law's observations. As to whether Mr. Law's explanation or whether his (Professor Edwards') was correct, time alone would show. He did not think, however, Mr. Law was justified in saying that manganese sulphide and carbide of iron did not give blisters ; at least he (Dr. Edwards) would not like to make such a dogmatic assertion. There were many people connected with the trade who believed that both manganese sulphide and carbide of iron would cause blisters. Of course, there were others who believed that something else was the cause of the trouble. To suggest that because carbide of iron was always present blisters should always occur, if that constituent could cause them, was quite misleading ; it all depended on the care taken in the pickling operation. For example, it was known that with proper care blisters could be avoided even in sheets which would give blisters when less carefully pickled. In tin plates the carbide of iron present always existed in the centre of the sheets, and there was a substantial thickness of material below each surface that contained no carbide.

He (Professor Edwards) was quite prepared to admit that the presence of one constituent might more readily cause the development of peppery blisters than another, but that did not affect the theoretical aspect of the question. The behaviour in that connection, if there were any difference, could easily be explained on the grounds that there must be a considerable difference in the cohesion between an iron-iron oxide surface of contact and an iron-iron carbide surface of contact : when it was remembered that blisters could be produced at the ordinary atmospheric temperature, it would be seen how difficult it would be to account for that by Mr. Law's theory. Further, it might be useful to point out that he (Professor Edwards) had produced a pickling blister containing as much as 100 cubic centimetres of gas and yet that blister was perfectly dry inside, and showed no trace of moisture. Surely that result could only be explained on the hypothesis put forward in the present paper.

Mr. Ridsdale raised the question of the effect of added reagents. Personally, he (Professor Edwards) carefully refrained from specifying what oxidising agents he had tried, simply because he did not want to mislead anyone into thinking that they could safely use any of them before they had been properly tested. He had not used Pickellette ; as a matter of fact, he had not used any of the patent pickling solutions, because he wanted to know exactly what he was doing, and to use such patent solutions for work of the kind described in the paper might be very misleading. He quite agreed with what Dr. Rosenhain said about the question of lateral diffusion. Fig. 6 was not intended to indicate the exact path of the hydrogen ; it was only intended to give a mental picture of what was going on, or something approaching it. In pickling, the hydrogen was developed on the side of the sheet, and

a large proportion of the hydrogen which entered the metal would diffuse at right angles to the surface at which it was generated. There was no suggestion in the paper that the hydrogen could only flow in one direction. Dr. Hatfield had made a very important point when he said that, in considering the embrittling effect of hydrogen on thin sheets, it was impossible to neglect the roughening of the surface by the acid. He (Professor Edwards) was endeavouring to work out systematically the embrittling effect of hydrogen, and was trying to make corrections for that varying influence of the surface. He was also extremely obliged to Captain Richards for the interesting observations he had made. Many of the figures that he had quoted would be exceedingly useful when they were embodied in the discussion on the paper. He was carrying out further experiments on special steels, such as Captain Richards suggested, with a view to determining the influence in that particular direction. The point the President had raised was a very important and interesting one. He asked why they should pickle in the usual manner if blisters were produced, whereas if the pickling were conducted electrolytically no such blisters were formed. There were many aspects of that question that could be dealt with. It was purely a question of convenience and cost. In most cases of boiler tubes or articles of that kind, where it was necessary to pickle, he would be inclined to recommend the use of the electrolytic method. Whether it was going to be possible electrolytically to pickle tin plates on a commercial scale or not, he did not know. He was arranging to carry out systematic experiments with a view of getting useful data in that direction. Members could easily imagine the enormous asset it would be if pickling could always be done electrolytically.

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### CORRESPONDENCE.

Mr. A. T. ADAM (Musselburgh) wrote that it was gratifying to see that the subject of pickling steel and the effect of hydrogen were receiving more attention. The embrittling effects of hydrogen on steel were sometimes extraordinarily disastrous. For example, he had frequently seen a coil of wire break up completely in the acid vat. Unfortunately, the matter had not so far been sufficiently studied to afford a reason for some steels being affected more than others. One of the worst cases of pickling brittleness he had known was that of a high-grade Swedish steel containing about 0.75 per cent. of carbon, and tests were made on the solubility of that steel in sulphuric acid, which showed that the steel was nearly ten times more soluble than usual. That appeared to confirm the author's results in Fig. 15, which showed that the rate of diffusion of hydrogen and the solubility could be closely correlated. Fortunately the attack of acids on steel

and the diffusion of hydrogen could be minimised considerably by adding certain substances of a more or less colloidal nature to the pickling vats, and it was interesting to note that the author had made some experiments on the influence of colloids and intended to extend those observations. There did not appear to be any very definite answer to the question of why the occluded hydrogen made the steel brittle. He understood one view was that the hydrogen caused a weakening at the crystal boundaries, and certainly pickling brittleness appeared to be typical intercrystalline brittleness, but he would be glad to have the author's views on that point.

Mr. A. ALLISON (Sheffield) wrote that Dr. Edwards' paper was a valuable one both from metallurgical and economical standpoints, and explored a field hitherto almost untouched. He quite agreed that hydrogen was the main factor in liberating scale, as he had frequently noticed the flakes of scale floating in the acid, and in cases where the temperature of the bath was kept low, there was a sediment of reddish oxide left when the vat was emptied. Dr. Edwards' experiments did not make quite clear the question of the penetration of hydrogen in the pickling time—namely, whether a longer pickling at a low temperature, or a short pickling at a high temperature would cause greater absorption of hydrogen. He (Mr. Allison) quite agreed that the action of the acid slowed up considerably with an acid strength over 7N. Also he found that when the sulphuric acid baths became rich in ferrous sulphate, pickling almost ceased when a specific gravity of 1300 was reached. In this case the addition of water caused an apparently exhausted bath to become active again. He considered that Dr. Edwards had proved his case as to inclusion arresting the hydrogen and catalytically reforming molecular hydrogen. In that connection he would like to have Dr. Edwards' view on the two photographic prints (Figs. 8 and 9, Plate IIIA). It would be seen that there were wavy white lines across the field.

Both steels were pickled, cold-rolled, and annealed. He had frequently noted that appearance in similar material, usually towards the outside, not particularly in the centre. It apparently had no detrimental effect on the steel. It just appeared possible that it was the after-effect of some hydrogen absorption, as pointed out by Dr. Edwards.

With reference to the more vigorous passage of hydrogen from a surface covered with oxide, he pointed out that annealed steels were far more difficult to pickle than plain hot-rolled steel. In close annealing, the oxides assumed a form—probably magnetic oxide—with a bright, almost metallic colour. That film was much more difficult to remove by acid, possibly being less porous.

He suggested that the interior of the pack of sheets, although one sheet apparently stripped the other of oxide, did not do so completely. In any case, the oxides and surfaces were in a similar condition to the





FIG. 8.

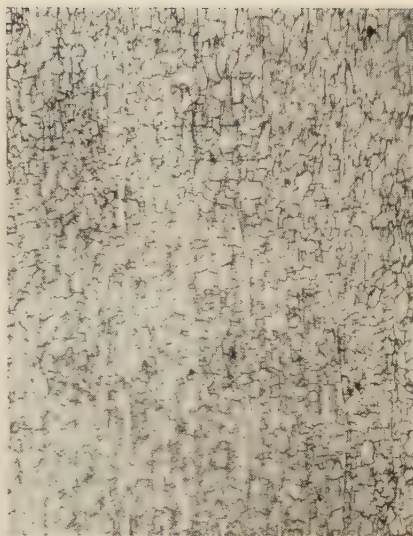


FIG. 9.

Pickled, cold-rolled and annealed material.





surface of close-annealed steel. The further experiments Dr. Edwards was making would, he hoped, lead to equally valuable results, and he would await the publication with great interest.

Dr. H. HARTLEY (London) wrote that the thanks of those interested in the use of pickled steel sheets were due to the author for his contribution to the knowledge of the subject. It was to be hoped that he would be able to continue that investigation, and that the further work foreshadowed in the present report would enable the difficulties with which he dealt to be eliminated. In the vitreous enamelling industry trouble due to sheet defects similar to those which he referred to as "peppery blisters" caused considerable difficulty. The defects might be classified under three headings :

- (1) Large blisters, generally noticeable after the firing of the first coat.
- (2) Series of smaller blisters in more or less straight lines.
- (3) Irregular blister development.

Faults (1) and (2) were generally admitted by both the enameller and the steel merchant to be due to defective metal, but neither was prepared to accept the responsibility for defects of the third type, which were the most common. From the point of view of the chemist it was, of course, very unsatisfactory to explain an enamelling fault as being due to "bad iron," as that appeared merely to be shelving the question. It was possible that defects of the third type were due to faulty enamelling, but in view of Dr. Edwards' work it seemed more than likely that many of those defects were really due to the metal itself. If the enameller complained that such a sheet were defective, the steel merchant's practice was to take the faulty sheet and send it to some friend in the enamelling trade, asking him to clean it and re-enamel it. Almost invariably a perfectly enamelled sheet was returned, and the steel merchant felt satisfied that the fault about which the complaint had been made was really due to his client's carelessness. The removal of vitreous enamel and the re-enamelling of the sheet did not really settle the point at issue. The fact that a blister had appeared in the enamel itself indicated that if the defect were due to the sheet, a minute perforation had been produced which enabled the imprisoned gas to escape. After removing the first enamel the sheet was in an ideal condition for re-enamelling.

Whilst the tenor of the above remarks might suggest that he (Dr. Hartley) was endeavouring to absolve the enameller from all blame and put the responsibility entirely on the steel-maker, that was not his object. It did not seem to be practicable to ensure that the sheets should be free from inclusions and from gas-pockets, and the preparation of an entirely satisfactory sheet would require careful treatment during pickling.

There was another class of enamel trouble which he believed to

be due to a large extent to a sheet defect. After enamelled plates had been in stock or in use for some short time it was sometimes found that the enamel chipped off in small pieces, leaving holes more or less circular in section and roughly about  $\frac{1}{4}$  inch in diameter. If the enamel were examined at the point at which the chipping had occurred, it would be noticed that the fracture was more or less conical, and often that both the cover coat and the ground coat had in part chipped off and at the apex of the cone the steel plate was exposed. If the visible steel were inspected it would be found that it had the appearance of a small pimple and could be punctured quite easily with a penknife.

Fig. 3 in the author's paper represented, he thought, the section through a sheet at such a point. It would be obvious that if a layer of enamel were superimposed on such a sheet as shown in Fig. 3 subsequent changes in temperature would cause a considerable strain in the vicinity of the projection and lead to chipping of the type which he (Dr. Hartley) had indicated. In the sign-plate trade it was often the practice to go over the plates carefully with an abrasive after they had been pickled and remove such small projections. In other classes of work where smaller articles had to be handled, it was not economic to subject the metal to such treatment.

If a sheet of mild steel which had been coated with a first coat of enamel were examined, it would be found that if the enamel had not been over-fired it was impregnated with small gas bubbles. It did not appear that those bubbles were due to gas generated by the enamel material itself. A vitreous enamel consisted of a flux which, for the present purpose, might be described as a soft glass, to which a small amount of clay, and in the case of a ground coat, often a trace of borax, was added at the mills during grinding. It was applied to the sheet in the form of a slurry, and after drying was "fired" (melted) by the insertion of the whole into a suitably heated muffle. Some water and possibly a little carbon dioxide, resulting from the combustion of any small amount of organic matter in the clay, was driven off during the firing, but that would not, he thought, explain the formation of the very large number of bubbles which could be seen on examination of a fired sheet. They were especially marked in an under-fired sheet and had largely disappeared from an over-fired sheet. It did not seem improbable that those bubbles were really hydrogen which had diffused out from the pickled metal. In certain laboratory experiments on enamel he had observed the bursting of bubbles which had formed during the firing, and had noted the production of flame due to the ignition of gas which had escaped from such bubbles. From the appearance of the flame the inclination was to regard the gas as carbon monoxide, but it did not seem improbable that it was hydrogen which had previously been secreted within the metal itself, as indicated in Dr. Edwards' paper.

The hypothesis advanced by the author appeared to him (Dr. Hartley) to be the most reasonable yet proposed. Some of the

criticisms made during the discussion of the paper did not appear to be entirely logical. Dr. Rosenhain stressed the importance of speaking of hydrogen ions diffusing through the metal, and later seemed to take exception to the double sheet experiments, on the ground that the author appeared to have overlooked the possibility of lateral diffusion due to non-intimate contact between the two sheets. The Edwards' hypothesis appeared to the writer merely to postulate that when hydrogen which had been diffusing through the metal crossed the metal boundary and entered another phase it was no longer capable of re-entering, or if it could re-enter the metal, the rate of re-entry became negligibly small. Collection of hydrogen could then occur in the neighbourhood of an oxide or other inclusion, and also at any point where there was a metal boundary within the material, as, for example, in any small cavity within the sheet. He (Dr. Hartley) demonstrated in Professor Bone's laboratory some twelve years ago that, in the case of certain metals, hydrogen and other gases readily entered the solid phase, and that gas which had been within the metal might cause the metal to become charged electrically when it diffused out. For example, silver and gold become negatively charged in atmospheres of hydrogen or carbon monoxide, and positively charged in an atmosphere of oxygen. The charge on the metal was influenced by the rate at which gas passed out from the solid phase into the surrounding gaseous phase. If Dr. Edwards' hypothesis were correct it should, by a slight modification of the dual sheet experiment and the actual provision of a small cavity between two sheets welded together, be possible for hydrogen to be collected therein up to a considerable pressure, and by making a suitable connection to the space between the sheets to arrange for that pressure to be measured.

With regard to the fact observed by Dr. Edwards, that the hydrogen generated in contact with the metal entered more rapidly when there was an oxide coating on the outer surface, might not that be due to the fact that when reduction of the oxide of iron resulted there was a decrease in molecular volume and an increase in the space through which the hydrogen particles could diffuse. As bearing on that point, it might be mentioned that when certain oxides—for example, copper oxide—were reduced by hydrogen the rate of removal of the hydrogen from the gas phase over an appreciable period was much greater than the rate of removal of oxygen from the gas phase when a stream of oxygen was passed over the recently reduced material, although it would appear that the *initial* rate of removal of oxygen might be as great as the initial rate of removal of hydrogen when passed over the oxide surface. The rate of removal of oxygen from the gas phase fell off very rapidly and the complete re-oxidation of the reduced material became a lengthy process. Apparently after the surface of the freshly produced copper had been oxidised, the rate of the diffusion of the oxygen into the deeper layer was much retarded. The difference in the rates of oxidation and reduction was not explained

by the difference in the densities of the hydrogen and the oxygen, as similar results were obtained with carbon monoxide and oxygen.

Professor EDWARDS wrote, in reply to the written contribution to the discussion, that he was particularly interested in the observations made by Mr. Adam, for they threw more light on another aspect of that very interesting subject. Whilst he (Professor Edwards) was not in a position to make any definite suggestion as to the cause of the peculiar effects noted by Mr. Adam, he now had some evidence which seemed to indicate that the rate at which hydrogen diffused through cold-worked steel was considerably greater than through the same steel when in the completely annealed condition. Further, there was also some evidence for believing that the rate of solution of the metal, in the acid, was greater under those conditions. It was just possible that something of that kind was the cause of the facts referred to by Mr. Adam.

It was very useful to have the contribution from Mr. Allison, especially in regard to the emphasis he laid on the facts relating to the effects of varying acid strength, and that of ferrous sulphate in solution. It was also helpful to have Mr. Allison's statement concerning the effect of water additions to solutions that were highly charged with ferrous sulphate, for that was a matter which was now being examined. So far as he (Professor Edwards) could judge from what Mr. Allison said about the two photomicrographs, he was inclined to think the lines were due to segregation in the original ingots.

He was especially pleased to have the communication from Dr. Hartley, for although it did not call for a reply it represented a most important and useful contribution, and drew attention to the importance of studying the action of pickling from the point of view of the enamelling trades.



## Iron and Steel Institute.

## THE EFFECT OF FREE SURFACES ON THE PLASTIC DEFORMATION OF CERTAIN METALS.

BY PROFESSOR F. C. THOMPSON, D.MET., B.SC., AND W. E. W. MILLINGTON,  
M.INST.C.E., M.I.MECH.E. (MANCHESTER).

Two papers already published by the present authors <sup>(1)</sup>, <sup>(2)</sup> have dealt with their views concerning the mechanism of the plastic deformation of those metals which crystallise in the face-centred and body-centred cubic lattices.

In the paper dealing with the body-centred cubic lattice, that of  $\alpha$ -iron, <sup>(2)</sup> reasons were adduced for the belief that the type of deformation in a single crystal should be different from that in a fine-grained aggregate. The differences were related to the restraint imposed by the crystal boundaries, where these exist, and pursuing the same line of thought the authors have in the present paper developed this idea and give reasons for believing that at the free surfaces of even an aggregate the deformation will probably differ distinctly from that within the mass. The whole subject is of fundamental importance in connection with the determination of the elastic limit and with elastic failure in general, and thus of interest both to the metallurgist, who is concerned with the testing of metals, and to the engineer who uses them.

Despite the criticisms which were levelled against the theory developed in the communications referred to, the authors see no reason up to the present to modify their original views, and these, so far as they bear on the present thesis, will be briefly summarised.

In close-packed cubic material ( $\gamma$ -iron and many of the non-ferrous metals) the deformation is considered to be effected, in its earlier stages, by the "easy-glide" of the atoms on the octahedral planes. Such movement appears of necessity to be restrained by the crystal boundaries, and at the free surfaces where there is partial removal of this restraint it is not difficult to imagine that

the atomic movement will be more easily initiated ; in other words, the elastic limit will be lower at the surface than it is internally. This conception is illustrated diagrammatically in Fig. 1.

There is also the possibility that at the surface the deformation may occur in planes other than that which is of importance within the mass, but of this there is no certain evidence.

In the case of  $\alpha$ -iron, and of other materials which crystallise in the same lattice, the effect of the free surface may be twofold. In the first place, there is the relative freedom from boundary re-

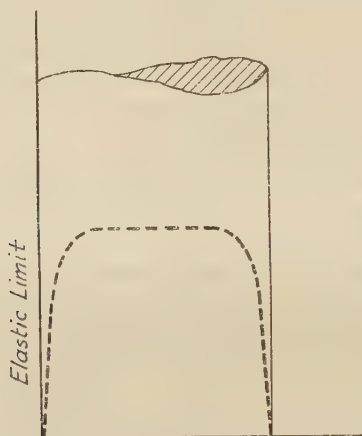


FIG. 1.

straint, which has already been considered above, and, in addition, good reason exists for the belief that movement will occur on the rhombic dodecahedral plane as distinct from the cube face, which is the normal. The evidence that cube face-movement is the usual type has already been given,<sup>(2)</sup> together with the theoretical and experimental reasons<sup>(3)</sup> for the belief that, in a single crystal, deformation proceeds on the dodecahedral plane. The difference is, in the authors' opinion, again to be ascribed ultimately to the surface effect. It at once follows that at any free surface the possibility of dodecahedral movement is apparently increased and must be taken into account. The effect of this surface deformation will be to produce plastic flow at stresses lower than that required within the body of the sample. This is the direct result

of the great probability, already considered,<sup>(2)</sup> that dodecahedral movement occurs much more readily than that on the cube face when the conditions are such as to allow it to proceed at all.

Evidence that the elastic limit is reached at the surface at a relatively low stress can be adduced from a number of different points of view.

Microscopically, Edwards and Pfeil<sup>(4)</sup> have demonstrated that, when subjected to definite tensile strain followed by a prescribed annealing, certain material produces large crystals within the specimen, but small ones over practically the whole of the surface. This can only be ascribed to the fact that the deformation required to cause excessive crystal growth on annealing, which was attained in the mass of the specimen, was not experienced at the free surface. This in its turn may be due either to the variation of the extent, or of the nature of the superficial deformation, or more probably to both. The belief of the authors is that at the surface the tension resulted in dodecahedral movement, which apparently is not, for some reason, suitable for subsequent growth, and that it was only within the sample that probable cube-face movement occurred which led later to the formation of large crystals. The investigators mentioned also showed the very striking fact that if the strain were imposed on the material by rolling instead of by tension, the surface behaved much as did the interior. They point out themselves that this is probably due to the restraint imposed by the surface of the rolls, which restraint is, in all probability, similar in its effects to that of the crystal boundaries, whence there should not be any difference in the behaviour of the surfaces and of the rest of the material.

The essential difference between iron<sup>(4)</sup> and aluminium<sup>(5)</sup> in respect of this surface film of small crystals points strongly to the fact that in the former metal the nature of the surface deformation differs in *nature* from that away from the surface, while in the close-packed metal the surface films of crystals, when they do occur, are more probably to be ascribed merely to variations in the *extent* of the preliminary deformation.

Micrographic evidence is thus in good support of the contention concerning the importance of the surface of a sample of metal under stress.

Passing on to the mechanical aspect of the subject, one very

important point at once arises. One of the methods which has been used for the determination of the elastic limit is the observation of the stress at which slip-bands first make their appearance. Now, if the foregoing conclusions are correct, such a method is practically valueless for the purpose. The slip-bands, being merely surface movements, can reveal nothing more than the stress at which deformation of that portion of the test-piece takes place, and thus they will have little bearing on the elastic failure of the specimen as a whole.

In this connection reference may be made to the work of Tammann.<sup>(6)</sup> For a large number of metals he determined the stress at which slip-bands were first formed, and also measured the elastic limit by ordinary mechanical means. The former stress was invariably very much lower than the latter, particularly so for copper, nickel, and zinc. A few typical results are collected in Table I.

TABLE I.

Metal.	Treatment.	I. Stress at which Slip-Bands first appeared. Kg. per Sq. Cm.	II. Elastic Limit (Mechanical). Kg. per Sq. Cm.	Ratio. II. I.
Copper .	Cast and slowly cooled	203	2780	13.7
Nickel .	Reheated 1 hour at 1350° C.	788	5570	7.8
Lead .	Cast and slowly cooled	25	102	4.1
Zinc .	Cast and slowly cooled	125	770	6.85
Iron .	Strongly annealed	2370	5840	2.5

The discrepancies in all of these cases are far too great to have been due to any ordinary cause. It is inconceivable that errors of 600 to 1400 per cent. should have been made in the determination of the elastic limit. From the point of view developed in the present paper, however, it is no longer unexpected that the two sets of figures should be so widely different; it is both what would be expected and required. It is clear that since copper, zinc, and iron all show the same effect, the deformation under stress of free surfaces is a phenomenon which is common to all metals, and is not a function of any specific crystal lattice. This does not mean, however, that the mechanism by which the result

is attained is not a variable dependent on the atomic arrangement of the particular material.

It may now be well to record the experimental evidence which it has been possible to collect and that has bearing on the point at issue. If elastic failure does occur initially at free surfaces, one of two conditions must obtain. In the first place, the elastic limit might be reduced by the smallest free surface to a low but definite value, which would then be independent of the extent of the surface. Although possible, such a state of affairs is *a priori* very unlikely, and it is much more probable that it should be possible to show that, as the cross-section of the specimen is reduced and the relative area of surface increased, the elastic limit falls. At the same time it must be remembered that the greater relative surface would be expected, as a result of the surface tension, to result in an increase of the elastic limit. Any observed fall of this value will have been actually reduced by an amount corresponding with the increase which would take place as a result of ordinary capillary phenomena. In amorphous material the effect of the latter forces is excellently shown for glass fibres by the following figures obtained by Griffiths <sup>(7)</sup>:

Diameter of fibre in inches .	0.04	0.00132	0.0005	0.000165
Tensile strength (lbs. per square inch) . . .	24,900	99,500	195,000	498,000

In crystalline aggregates the effect due to the free surface is in the opposite direction, despite doubtless a similar tendency to increase due to the surface tension. This means, of course, that even small reductions of the elastic limit as the cross-section of the specimen is reduced can only be interpreted as meaning a much larger tendency to fall, so far as purely crystalline effects at the surface are concerned. The evidence available shows an unmistakable fall in spite of the opposing capillary effect.

The following figures are all taken from Unwin's book on "The Testing of Materials of Construction," 1910, and though not in all cases free from objection through lack of information concerning the composition and treatment of the material, all point in the same direction as that demanded by the hypothesis under consideration.

A mild steel bar, recorded on p. 122, was strained to the yield point and then annealed at 750° C. The yield point after this



treatment fell as the diameter of the test-piece decreased, as is shown below :

Diameter in inches . . . . .	0.749	0.715	0.689	0.672
Yield point (tons per square inch) .	7.54	7.15	6.88	5.79

The elastic limits of wires of the following composition, all being in the annealed state, are given on p. 348 of the same volume :

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	
0.115	...	0.41	...	0.072	
Diameter in inches . . . . .	0.31	0.26	0.23	0.20	0.16
Elastic limit (tons per square inch) .	21.4	20.4	19.9	20.9	18.8

The general trend in both these cases is in the required direction. The same effect is also shown for steel rails of different sections on p. 342. Since in this case the smaller sections will have cooled, if anything, more quickly than the larger ones, apart from the surface effect, the elastic limit would be expected to be higher rather than lower. The full analyses are not given, but the carbon content of all the rails recorded below was  $0.37 \pm 0.02$  per cent.

Sectional area in square inches . .	6.02	6.60	7.34	7.70
Elastic limit (tons per square inch) .	17.1	19.9	18.5	21.8

Finally, on p. 339 mean values are given for sheets of varying thickness :

Thickness in inches .	0.12-0.13	0.13	0.14-0.20	0.18-0.20	0.23-0.30
Yield point (tons per square inch) .	16.6	19.3	24	23	31

It will be noted that the direction of the variation is again that required.

It would probably be possible to discredit any one of these sets of figures, but since they all point in the same direction and to the conclusion that as the surface increases the elastic limit falls, the combined value of all the results is cumulative. There is, however, stronger evidence available.

Dalby<sup>(8)</sup> records the following values of the yield point for five test-pieces all geometrically similar and all turned from the same bar,  $1\frac{1}{4}$  inch diameter, of 30-ton steel :

Diameter in inches . . . . .	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$
Yield point (tons per square inch) . . . . .	20.9	20.3	21.4	21.3	22.6

There is a progressive rise as the diameter is increased, which is the reverse of what would be found if segregation were responsible for the variation. Since the diameter, even of the largest test-piece, is  $\frac{1}{2}$  inch less than that of the bar from which it was

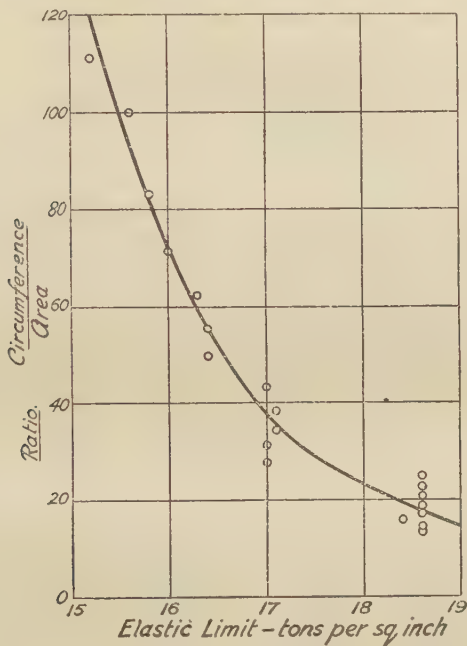


FIG. 2.

prepared, any slight cold-working will, in all probability, have been removed.

The best evidence which the authors have, however, was very kindly supplied by a friend who wishes to remain anonymous. The material consisted of wires of the following composition :

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.
0.65	0.125	0.56	0.039	0.034

All the wires had received the same final annealing at 750° C. in pots filled with iron turnings. The full data supplied are recorded in Table II., although it is to the elastic limits that attention is specially drawn. In Fig. 2 the elastic limit is plotted against the

rates of the circumference to the area of the wire, and the influence of the surface is very clearly seen. The figures supply as complete a proof as could well be desired of the main contention of this paper, that elastic failure is controlled by the free surfaces.

The structure of all the wires was one consisting of sorbitic pearlite and ferrite, with no appreciable alteration from one end of the series to the other. The elastic limit variation is not, therefore, due to the structure, but to the surface. The typical structure is shown in Fig. 3 (Plate IV.). The constancy of the maximum stress is of interest.

TABLE II.—*Physical Properties of Annealed Steel Wires of Varying Diameters.*

Diameter. Inch.	Tons per Square Inch.			Elongation per Cent. on $4\sqrt{\text{area.}}$	Reduction of Area per Cent.
	Elastic Limit.	Yield Point.	Maximum Stress.		
0.300	18.6	24.0	34.5	35.0	62.0
0.276	18.6	24.2	35.0	35.1	63.0
0.252	18.4	24.1	34.6	35.0	63.0
0.232	18.6	23.9	35.1	35.1	63.2
0.212	18.6	24.0	34.8	35.1	63.2
0.192	18.6	23.2	34.9	38.4	64.0
0.176	18.6	24.0	34.7	35.3	64.0
0.160	18.6	23.4	35.0	35.3	65.2
0.144	17.0	23.0	35.0	36.0	65.4
0.128	17.0	22.8	35.0	36.0	66.3
0.116	17.1	22.2	35.0	36.0	66.5
0.104	17.1	22.3	35.0	36.0	67.0
0.092	17.0	21.8	34.6	36.8	67.4
0.080	16.4	21.2	34.2	38.0	69.0
0.072	16.4	20.9	34.2	38.0	69.1
0.064	16.3	20.4	34.2	39.2	69.1
0.056	16.0	20.4	34.2	39.4	70.2
0.048	15.8	20.1	34.2	41.4	70.6
0.040	15.6	19.8	34.1	41.4	70.3
0.036	15.2	20.0	34.1	42.5	71.2

Other important evidence is available that where the surface is enabled to move, plastic deformation may there be obtained under stresses far below those normally considered to be the elastic limit. Very recently Handford,<sup>(9)</sup> working under Professor Desch, has published an account of a thermionic valve method of detecting surface slip, and among the few results recorded reference may be made to the following:

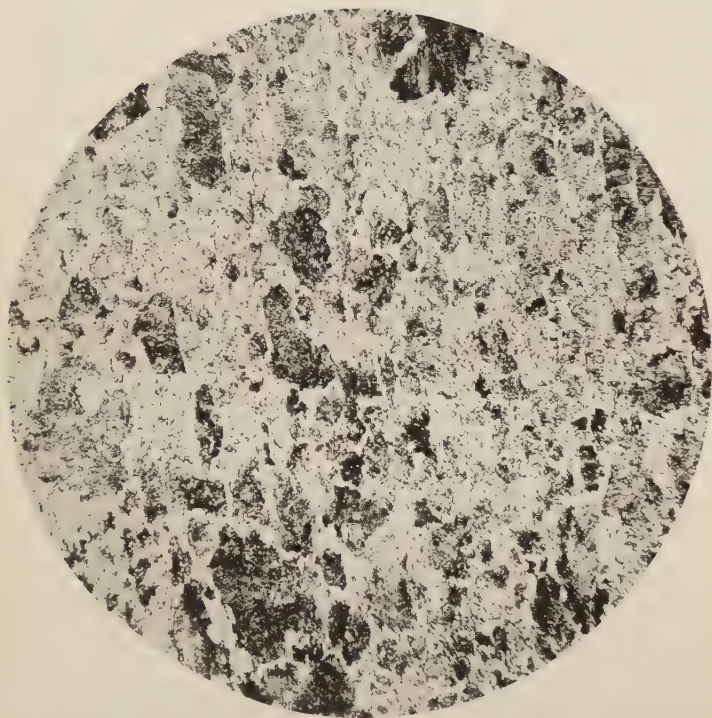


FIG. 3.— $\times 200$ .





Material.	Safe Range of Stress in Haigh Fatigue Test. Tons per Square Inch.	Elastic Limit. Tons per Square Inch.	First Surface Movement detected in Valve Test. Tons per Square Inch.
70 : 30 brass . . .	10·0	2·7	2·4
0·25 per cent. carbon, acid open-hearth steel . . .	24·0	16·0	14·2
Annealed copper . .	11·5	4·0	0·1-0·4
Annealed nickel . .	37·0	25·0	0·6

The elastic limit was determined by visual methods, or with the Metzger extensometer. It is, to the authors, inconceivable that in an aggregate the values recorded for the first surface movement should be the true elastic limit, especially in the face of the values for the fatigue ranges also given. The conclusion is thus drawn that what was determined in these tests was merely that stress at which movement, "easy-glide" in the non-ferrous materials, or rhombic dodecahedral movement in the iron, took place on the surface, which bears no relationship to the stress at which elastic failure would result in the metal as a whole.

Attention may now be drawn to the bearing of the ideas developed on fatigue testing, chiefly in the light of the work published by Gough, which is taken as representing the best at present available.

In the most general case as the stress is increased the surface begins to deform, owing to the lack of a portion of the boundary support. Under any circumstances—that is, whether the metal under examination crystallises in the face-centred or the body-centred lattice—this deformation results in a stiffening up of the material which has undergone movement,<sup>(1), (2)</sup> until it becomes capable of supporting the load applied. This also has the effect of imposing strains, probably elastic, on the interior of the mass. When this stage has been reached, although permanent set has occurred, the material is still within the fatigue range, and is actually more capable of withstanding the load than it was previously. With a further increase of stress the same process is repeated, and the material may be stiffened up to the stresses by gradually building up the load, exactly as Gough<sup>(10)</sup> has so well shown experimentally. The process described cannot proceed

indefinitely, however, since the interior, as pointed out above, is subjected to gradually increasing internal stress, and, as the external load is increased, at some point this, together with this internal stress, imposed by the superficial movement, will reach a value at which failure ensues, and the fatigue limit will then be reached. If, now, this be the course taken by the test, it becomes possible to predict another experimental result. In tests of the Wöhler type, and those involving alternating torsion, the maximum stress is applied at the surface, and any effect due to the free surface should be a maximum. If a stress-strain curve be plotted, then as surface movement proceeds and the specimen is strengthened by it, the deflection of the test-bar will be less than that expected from the earlier deflection by some amount corresponding with this increase of rigidity. This means that the deflection curve should incline towards the stress ordinate more than would be expected, apart from surface effects. This bending has been observed, and Gough reproduces an excellent curve (Fig. 7 of his paper) showing it. So far as the authors know, no adequate explanation of this has hitherto been available.

The same effect as that just referred to, and noticeable in Figs. 7, 12, and 12A of Gough's paper, is shown by results obtained by Gough and Hanson.<sup>(11)</sup> In their Fig. 1 is recorded the normal straight line stress-strain curve for tension and compression of Armeo iron. Alongside of this curve, however, is also given one for the permanent set. The latter, which is measurable from less than 2 tons per square inch, increases gradually as the stress rises. It thus follows that the elastic portion of the stress-strain curve cannot be linear, since the observed curve is the sum of this elastic deformation and that due to the permanent set. Hooke's "law" is, therefore, merely empirical, and though of sufficient accuracy for most practical purposes, is not true, and the true elastic stress-strain curve for a metal should bend away from the stress ordinate. The limit of proportionality, even where this is to be found, is thus a perfectly meaningless value. The authors have previously given reason<sup>(1)</sup> for the belief that Hooke's "law" did not hold up to the elastic limit, and the evidence just given is further strong support in this direction. It is now possible to postulate further that one, at any rate, of the reasons for this deviation from the straight line stress-strain curve is the preferential flow observed at the surface

under stresses too small to affect, other than elastically, the central portions of the sample.

The following paragraph taken from the paper <sup>(10)</sup> already mentioned is of the greatest interest in connection with the effect of free surfaces on fatigue tests :

“ It is well known that if endurance tests are carried out on solid and hollow specimens under reversals of bending stress by the Wöhler method, and the maximum stresses are plotted against the number of reversals for failure, both curves ultimately become asymptotic to the same value of the limiting stress, but at widely different values of the reversals.”

In such work the initial failure of the surface layers commences at values of stress below those at which the remainder begins to fail, and thus accelerates the rate at which the fatigue occurs. The fact that the additional surface available in the hollow specimens does not modify the value of the fatigue limit is evidence that the surface effect is merely the initiating cause of the failure.

The swing back of the curve below the elastic limit which has been dealt with above is, in the foregoing instances, quite regular and the curve is smooth. At the same time, there is no obvious reason why this should be so, since it is quite easy to imagine that the surface might fail in a series of jerks. This latter case is excellently illustrated in Fig. 13, of Gough's paper, dealing with Armco iron, where a quite large peak is shown in the curve well below that stress at which the curve bends right away, and at which the thermal fatigue limit is indicated. It is of interest that Gough appears to consider that this is an abnormal effect, since he does not worry to give the actual value of the stress at which it takes place. If that be so, the authors are in complete agreement with him on this point, and further offer the explanation above. When surface failure takes place it must stiffen up the material on their hypothesis, and this will cause the curve to return to a lower value of the deflection than that which obtained before the change had commenced.

Again, the same surface failure may very well be also responsible for the fact that if a thermocouple be applied to a specimen of nickel subjected to a range of stress considerably less than the fatigue range, large bursts of heat occur which rapidly die away. Haigh has observed this effect in several materials. No adequate

explanation has hitherto been offered for these facts, which fit in excellently with the authors' requirements. Further, if the latter are correct, it simplifies matters considerably, since these initial heat bursts have little to do with the final fatigue failure. They merely represent surface phenomena, and the reflection of the latter upon the mass, which stiffen the material and thus enable it to resist further applications of the stress responsible for the previous movement.

It is but fair to point out, however, that Gough and Hanson have realised clearly that effects of some kind may make a transitory appearance, and may be without effect on the final breakdown. They do not, however, appear to have had any very clear conception of the origin of such phenomena.

Gough's work also points to the conclusion, which is not unexpected, that in the ferrous materials the softest irons consisting entirely of ferrite are much more sensitive to the effect of free surface than the harder ones, in which pearlite or sorbite is the preponderating constituent. Finally, his Table I., which gives results obtained on solid and hollow specimens of a 0.65 per cent. carbon steel under reversed shear stress, shows the effect of the greater surface of the hollow specimens excellently. The range of stress required to produce fracture after three million reversals, a stress which is certainly higher than the fatigue limit, at any rate for the solid specimens, is given as follows :

Solid specimen	.	.	.	.	± 13.5 tons per square inch
Hollow specimen	.	.	.	.	± 10.5     "     "     "

There is reason to believe that, under compression stresses, the effect of free surface should be even greater than it is in the case of tension, since in compression the tendency is for the material to flow out at the surface, whereas in tension it moves as a whole inwards. Our knowledge of the effects of compression is certainly far less satisfactory than in respect to tension, and the work of Coe <sup>(12)</sup> is the more valuable for this reason. The predominating characteristic of his results is the very low value obtained in almost every case for the elastic limit in compression. For cast or annealed material the values are extremely low, with the two exceptions of iron and nickel, where they approximate to 8 tons per square inch. It is clear from the behaviour of metals in service,



and under alternating tension and compression, that such loads do not represent the stress at which the material as a whole will fail elastically. The authors, therefore, find in his results further proof of the surface yielding at stresses far below those at which the mass as a whole becomes plastically deformed, which they have already shown to be the case for tension.

One very elegant proof of the importance of free surface on plastic deformation in compression may be recalled, which goes very far towards confirming the suggestion that without initial surface failure a material would stand up to almost infinite stresses. Jeffries<sup>(13)</sup> has shown that when aluminium and an aluminium-copper alloy are subjected to hydrostatic pressure, there is neither deformation nor hardening. The pressure applied, 12,400 kilogrammes per square centimetre, about 80 tons per square inch, is some three times the tensile strength of the material as normally obtained, and yet clearly the elastic limit had not been reached.

One other aspect of the micrographic evidence in favour of the importance of free surfaces on elastic failure in compression may be mentioned. In the case of a transformation which involves change of volume, such, for instance, as the transition from austenite to martensite, the commencement of the change normally occurs at the surface, and even where the conditions have been such that a considerable amount of austenite is retained internally nothing but martensite is found at the surface. Benedicks<sup>(14)</sup> has dealt very fully with this question, and shown that the explanation is to be found in the surface as such. If the present authors were right in their previous explanation of the formation of martensite,<sup>(2)</sup> this constituent could not be formed until stresses equal to the elastic limit of the austenite have been set up. This follows from their suggestion that martensitisation is initiated by the commencement of "easy-glide" in the austenite. This stress will, in terms of the present hypothesis, be least at the surface, and hence it is here that martensite would be expected. Benedicks also showed that by imposing such a restriction to surface movement as is implied in a jacket of white cast iron, austenite remains right up to the surface. This is again exactly comparable with Jeffries' results, in which surface compression retards movement and so raises the elastic limit.



In conclusion, it may be said the authors feel that, under all stresses, but especially in compression, the effect of free surfaces is of vital importance in connection with elastic failure.

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*DISCUSSION.*

Dr. D. HANSON (National Physical Laboratory), in opening the discussion, congratulated the authors on a very interesting and suggestive piece of research, with the results of which he found himself more in agreement than he had been with those contained in their last two papers. At the same time, he was not prepared to go quite so far as they did in the matter. He could not admit that all evidence adduced from the appearance of slip-bands on the surface of a piece of metal was useless in arriving at the elastic limit of the material. It might be that the surface layers had a somewhat lower elastic limit than the interior portions of a test-piece, but the surface could only stretch so far as it was allowed to by the elastically strained interior of the test-piece; so that no matter what the elastic limit of the outside, the total strain could only be equal to the total elastic strain in the interior, and that was a very small amount. If very well-marked slip-bands were obtained on the surface of a piece of metal, it could be taken as evidence that not only had the outside layer moved, but the inside as well. The type of slip-band he would expect to find if the outside skin were only stretched as much as the elastic deformation of the interior would be so small as to be practically undetectable under the microscope. Nevertheless, the suggestion that the outer layers had a somewhat lower elastic limit than the interior more restrained portions of the piece of metal was interesting, and he thought might be quite well founded. He desired to deal with one or two questions of detail in connection with the experimental results that the authors produced. In the first place, the table on p. 69 gave the safe range of stress, the elastic limit, and the first surface movement stresses for a number of materials. He had no quarrel with the authors' figures for brass and open-hearth steel, but their figures were quite wrong for copper and nickel. Annealed copper was stated to have a safe range of stress of 11·5 tons per square inch, but an elastic limit of 4 tons per square inch. The latter figure was surely much too high. The elastic limit of properly annealed copper was so low as to be indeterminable on the ordinary extensometer tests. Personally, he would say the elastic limit was not more than one-tenth or two-tenths of a ton at the most. In the case of nickel, he thought the authors had made a still more serious error. In the first place, the fatigue range of pure nickel was nothing like so high as 37 tons per square inch; it was of the order of 24 to 26 tons per square inch; a well-marked yield point occurred at about 8·0 tons per square inch, and the elastic limit was much below that. The differences which the authors suggested existed in those cases were therefore very much less than the figures given. He thought it would be correct to say that

the difference between the elastic limit and the first surface movement in the case of pure copper and pure nickel was very small. He hoped the authors would look into those figures before they replied in writing, because he thought it would be a great pity to let them stand if what he had said was correct. With regard to the question of heat bursts during fatigue test, he did not think the evidence the authors adduced in the paper was by any means conclusive in support of their theory. Heat bursts could be accounted for more easily by assuming that the metal was deformed not only at the outside, but throughout its mass. The work done in deforming the metal would cause the bursts of heat, whether on the surface or inside. The view of Gough and himself was that the heat was generated by general deformation throughout the material. Perhaps in the very early stages the surface might be the only part that entered into it, but at stresses much below the fatigue limit he believed the mass of metal was deformed, and not only the surface. Finally, he would like to suggest that failure of a piece of metal did not necessarily take place at the outside, as the authors seemed to suggest. That was particularly the case in pure tension. He thought a pure tension fracture more usually started in the centre of the material, and a weak outside layer did not seem to explain the mechanism of the formation of a test-piece in tension.

Professor C. A. EDWARDS (Swansea) said the authors dealt with a subject which was capable of being experimentally tested, and yet had not carried out a single experiment. He appealed to them to cultivate patience, and make a serious effort to obtain the experimental evidence usually associated with scientific inquiry. It would have been much better if they had waited to obtain the results of some experiments of their own, so that it might be possible to judge how valuable their views were. Perhaps the answer to that was that evidence was given in the paper, but he asked the members to examine such evidence as was given. The authors quoted some figures from Unwin's book. He (Professor Edwards) had consulted Unwin's book again, and he found that the first set of figures was utterly useless from the point of the influence of the diameter upon the yield point. Unwin took a specimen, strained it, and obtained the yield point in that condition; then he annealed it, strained it again, and obtained the yield point in that condition, and repeated the process eight times. At the end of his experiment he had therefore a specimen which had been strained and annealed eight times, and, it had to be borne in mind, strained to that particular degree and annealed at that particular temperature which it was now known was associated with crystal growth. Hence in those tests the effects of repeated annealings and strainings were being tested, and not the influence of the diameter of the specimen. In the next set of figures the authors referred to wires. If reference were made to those figures it would be found that the most remarkable feature about them was their inconsistency. He

thought there was only one figure that was really in line with what the authors would like to have, namely, the last ; but there was still more to be said about that in connection with what the authors considered to be the best set of figures they had. If the analyses, so far as they were given, by Unwin were consulted, in the next set of figures it would be found that the carbon variations were in accordance with the changes in the yield points. There were figures given for the phosphorus or manganese content, and in view of that fact the figures were utterly useless for the authors' purpose. The next set of figures for thin tin sheets were not even accurately recorded. He had the set of figures with him, but if they were read as they were given in the paper it looked as though the yield point was fixed, but in Unwin's book, for each set there was an indication that the yield point varied from 14 to 16.6, from 15 to 19.2, and so on. The authors had taken the maximum figures, for which there was no justification at all.

In the next set, quoted from Professor Dalby's works, there was only one that was of any use ; the others were well within experimental error, and they were not all in the direction that the authors would like them to be. Turning now to the best set of figures, on the face of them they looked quite satisfactory, but they were not really so when they were examined. It was true that the figures varied in accordance with the diameter ; but how did the authors know that it was only the particular kind of surface effect they were looking for that was being examined ? Possibly it was a surface effect in one direction or another, but not necessarily in the direction that the authors supposed. The specimens had been worked to different degrees, and the facility with which that work came out on annealing varied with the degree of work that was put upon the specimen. The wires had been annealed in different pots. Although the annealing might be quite reliable from a commercial point of view, it was impossible to rely on a commercial annealing when an endeavour was being made to pick out very small differences. It was necessary to have scientific annealing in dealing with scientific questions. Further, in a box, even if it was the same box for the different annealed wires, it could not be said that the variations described were due to the effect of the surface crystals themselves, because annealing operations, even in iron borings, were not really inert. There were differences in the ratio of surface to mass in the various wires to start with, and the gases in the boxes might affect the wires to different degrees, according to their diameters.

The theory put forward by the authors in their paper was a very interesting one. It was one which all metallurgists would more or less expect, because evidences of yield before the elastic limit had been recognised for a long time. He (Professor Edwards) had confined his remarks to the tensile, and did not think he need say anything more about that, other than that the authors might have made a tentative calculation of the influence of surface crystals in that connection,



when he ventured to think they would have found it could not be sufficient to be experimentally detected in ordinary specimens of steel.

It was pointed out by Pfeil and himself that it did not necessarily follow that because surface crystals were obtained with iron and not with aluminium there was a fundamental difference in the deformation. It was necessary to remember that Professor Carpenter annealed his specimens at  $500^{\circ}$ , which was very near the melting point, whereas Mr. Pfeil and himself could not anneal theirs above  $900^{\circ}$ , which was at a much lower relative temperature. If it had been possible for them to get the same relative temperature in relation to the absolute melting point, then it might have been possible for the surface crystals on iron to be absorbed.

Dr. W. H. HATFIELD (Sheffield) said that Professor Edwards had said practically everything that he would have liked to say. He agreed with the remarks Professor Edwards had made, and thought Professor Thompson should not have taken the evidence of Table II. seriously. The variables introduced in manufacture were such as entirely to disqualify those figures from any serious consideration.

Dr. THOMPSON, in reply, said that in view of the shortness of the time available he would reply to Dr. Hanson's remarks in writing, and confine his verbal reply entirely to Professor Edwards' remarks, because apparently they opened up the most serious issue. Professor Edwards, who had criticised the data provided in the paper, appeared absolutely to have missed the paragraph which showed that the authors were at least as fully aware as he was of the uncertainty of some of the experimental evidence given prior to Table II. The authors stated definitely on p. 66: "It would probably be possible to discredit any one of these sets of figures, but since they all point in the same direction and to the conclusion that as the surface increases the elastic limit falls, the combined value of all the results is cumulative." He thought both Mr. Millington and himself would be perfectly prepared to cut out the whole of the figures on p. 66, and still stand absolutely by their theory. In the first place, no criticism had been levelled against the very interesting and, he thought, incontrovertible results obtained by Dalby, which were given at the bottom of p. 66. The criticism of Professor Edwards, supported by Dr. Hatfield, with regard to the figures on p. 68, controverted itself on the face of it. Professor Edwards had pointed out how many irregularities could conceivably crop up, and yet if those irregularities occurred the obvious and only possible conclusion that could be arrived at with regard to them would be that the results would be exceedingly erratic, and, instead of falling absolutely on a fair curve, would be all over the place. It only required a few minutes' serious attention to the point in question to realise that Professor Edwards' criticism refuted itself. If the members looked at the curve plotted in Fig. 2 they would find



that those points, instead of being all over the place, fell absolutely on a curve which followed the line that the authors' theory demanded. Incidentally, the maximum experimental error of temperature was certainly less than  $10^{\circ}$  in that particular case. It was only necessary to look at the results in a fair spirit to realise the fact that the irregularities which had been brought into consideration could not play any serious part at all. He desired to emphasise the point, however, that Professor Edwards' criticism referred to only one section of the paper. If the paper consisted of those figures by themselves, the criticism would be stronger than it was, but Professor Edwards did not in any way touch upon any of the other points that had been introduced. The results of Tammann and Handford, the appendix on the quenching of steel, and the results of Jeffries on the effect of hydrostatic compression, pointed in exactly the direction that the authors required them to point. Further than that, Professor Edwards ultimately proceeded to a consideration of the compression of the surface crystals in iron and aluminium. Personally, he (Dr. Thompson) was not at all sure that it would not be possible to cut out the compression of the aluminium crystal altogether. In that connection he would summarise very briefly what Professor Edwards and Mr. Pfeil themselves had obtained. They showed that when the peculiar crystals of iron, which they so beautifully obtained, were produced by ordinary tension, whatever the cause was, the surface crystallisation was different from that at the centre, except in those cases in which they had applied more compression at the surface by rolling. Professor Edwards' own work on the subject was, perhaps, the strongest piece of evidence that could be wished for that the surface deformation was different from the deformation at the centre. That, very briefly, was the position the authors took up. First of all, they were fully aware of the irregularities possible on p. 66, but it was to be emphasised that they all pointed in the same direction. He thought he had completely replied to the question raised in regard to the irregularities in annealing of the wires. Those wires were admittedly annealed under commercial conditions, but they were annealed as carefully as it was possible to carry it out. If the irregularities which Professor Edwards suggested existed, it would have been impossible for all the points that were obtained to fall so beautifully on the curve. Finally, Professor Edwards' own work on the big crystals of iron appeared to be as strong a confirmation of the authors' own theory as it was possible to imagine.

## CORRESPONDENCE.

Mr. U. R. EVANS (Cambridge) wrote that Professor Thompson and Mr. Millington's paper would seem to establish a fact of great importance—namely, that in a polycrystalline specimen deformation commenced more easily at the surface than in the interior. That could, however, be accounted for in a manner independent of the authors' special theory of "easy-glide," and the alternative explanation might perhaps appeal to anyone who might not have accepted the "easy-glide" view in its entirety.

As pointed out elsewhere,<sup>1</sup> the elongation by gliding of a "single-crystal" rod of metal need not involve any disorganisation of the crystal structure, although a "stepped" outline would necessarily arise at the boundary of the specimen, where the various slices had glided relatively to one another; the only work done—other than against friction—was accounted for by the slight increase in the surface energy connected with the increase of surface. But in a polycrystalline specimen the "steps" which would have to appear at the edges of contiguous crystals, in the event of that regular gliding, would not, in general, fit in with one another; hence of necessity there must be some disorganisation of the stable crystal array at the grain boundaries, and probably on the gliding-planes also. That that really occurred was confirmed by the fact that when specimens of worked metals were annealed, recrystallisation (the return to the stable array) commenced first at the grain boundaries, as found by Carpenter and Elam<sup>2</sup> in aluminium, or along the gliding-planes, as found by Adcock<sup>3</sup> in cupronickel. It was preferable to assume that deformation had produced gradual disorganisation in those regions rather than to postulate the formation of a definite "vitreous phase," as suggested by Beilby; for the "probability" of recrystallisation occurring within unit volume seemed to increase gradually, not only with the degree of deformation, but also with the temperature of the subsequent annealing, as had been indicated by researches on several metals carried out recently by Dr. Cook and the writer.<sup>4</sup>

Clearly additional energy would be needed during the elongation of a polycrystalline specimen to bring about the disorganisation referred to; thus, owing to the mutual interference of contiguous crystals with regular gliding, the stress needed to cause permanent deformation in a polycrystalline specimen would exceed that needed

<sup>1</sup> U. R. Evans, *Journal of the Institute of Metals*, 1921, vol. xxv. p. 298.

<sup>2</sup> H. C. H. Carpenter and C. F. Elam, *Journal of the Institute of Metals*, 1921, vol. xxv. p. 259.

<sup>3</sup> F. Adcock, *ibid.*, 1922, vol. xxvii. p. 73.

<sup>4</sup> M. Cook and U. R. Evans. Paper about to be published in *Transactions of the American Institute of Mining and Metallurgical Engineers*.

in a single crystalline specimen. Hence, the strength of the single-crystal specimens would be less than that of polycrystalline specimens, as found by Carpenter and Elam,<sup>1</sup> whilst, in comparing different polycrystalline specimens of the same grain-size, the more slender specimens would have a smaller apparent yield-stress than the stouter specimens, as indicated clearly in the present paper.

It should not, however, be forgotten that during the stressing of a bar of any material—whether crystalline or glassy—the load per unit area applied to the surface would in general be different from that applied to the interior. Where surface blemishes occur, the local force per unit area might vastly exceed the average force per unit area in the interior.

Dr. THOMPSON and Mr. MILLINGTON wrote, in reply to the correspondence, and in further reply to the oral discussion, that they were glad Dr. Hanson was in general agreement with their conclusions, even if his approval were a little qualified, especially so as his work with Gough had been freely considered. With regard to his main point, that the surface could only stretch so far as it was allowed to by the elastically strained interior of the test-piece, they were in general agreement. At the same time that did not necessarily mean that the elastic limit at the surface was merely fractionally lower than that within the mass. An outer layer with a low elastic limit would not move appreciably, though it might well deform sufficiently to show slip-bands, so long as it was supported by a stronger interior, but it would mean that that interior would have to carry more of the load—namely, its own share and most of that of the surface portion. The points which the authors wished to make, if the surface layer, owing to lack of support externally, was less able to withstand stress than the material as a whole, were :

1. In those cases where the maximum stresses, by ordinary calculation, existed on the surface, as, for example, in bending and torsion, the stress distribution would be very materially affected and definite elastic failure of the surface layers might take place before the interior failed elastically.

2. In those cases where the stress distribution was supposed to be uniform over a section, as, for example, in an ordinary tensile test, elastic failure of the surface, such as would be revealed by an extensometer, probably would not take place before that of the bar as a whole. At the same time, the weakness of the surface layer must necessarily throw more stress on the interior and, whilst that interior would have the same elastic limit in all cases of identical material, the elastic limit of the specimen as a whole, calculated on the assumption of an even stress distribution over the *whole* section of the bar, would decrease as the proportion of the weak outer layer to the interior increased.

<sup>1</sup> H. C. H. Carpenter and C. F. Elam, *Proceedings of the Royal Society*, 1921, vol. c. [A], p. 329.

To make that point clear let,

$D$  = diameter of a test-bar ;  
 $\delta$  = thickness of the weak outer layer ;  
 $t$  = elastic limit of the bar as a whole ;  
 $t_1$  = elastic limit of the interior ;  
 $t_2$  = elastic limit of the outer layer ;

then

$$\begin{aligned}\frac{\pi}{4} D^2 t &= \frac{\pi}{4} (D - 2\delta)^2 t_1 + \frac{\pi}{4} \{ D^2 - (D - 2\delta)^2 \} t_2 \\ \therefore t &= \left(1 - \frac{2\delta}{D}\right)^2 t_1 + \frac{4\delta}{D} \left(1 - \frac{\delta}{D}\right) t_2 \\ \therefore t &= t_1 - (t_1 - t_2) \left\{ \frac{4\delta}{D} - \frac{4\delta^2}{D^2} \right\}\end{aligned}$$

From that equation, clearly if  $t_1$ ,  $t_2$ , and  $\delta$  were constant,  $t$  increased as  $D$  increased.

Concerning Dr. Hanson's second point, with regard to the values of the fatigue limit in the copper and nickel, the authors would point out that the figures were not theirs, but were obtained, as mentioned in the paper, by Handford working under Professor Desch. It was probable that the two metals mentioned were by no means pure, but that fact did not affect the value of the results to the authors. The results, on whatever were the metal, showed beyond doubt that in all the samples quoted the stress at which the first signs of permanent surface failure occurred was far below the ordinary working stresses, and also very far below the values given for the fatigue ranges. The heat bursts, to which reference was made by the same speaker, might in part be due to deformation of the metal in the interior of the test-piece, but if it were conceded that the initial stages of the deformation were purely surface, as Dr. Hanson appeared to be willing to do, their point was satisfied—namely, that they, the heat bursts, were due initially to surface movement, and that in the absence of free surface such deformation would not occur. The final point made by Dr. Hanson, that ultimate breakdown of the metal occurred at the centre of the test-piece, might very well be true. As Merrills<sup>1</sup> had pointed out, however, that was no evidence that the elastic failure took place there. That point had been specifically dealt with by the author mentioned, who quite independently of the authors, and from purely experimental grounds, came to the conclusion that the seat of the elastic failure was, in the first instance, the free surface.

Passing on to a further reply to Professor Edwards' discussion, the authors desired in the first place to emphasise that the appeal to them to cultivate patience was perhaps a little unnecessary. For fully two years the authors had been considering the subject-matter of the paper, and it was not until they were sure of their ground that anything

<sup>1</sup> *Carnegie Scholarship Memoirs*, 1924, vol. xiii. p. 83.



had been mentioned. The remarks that they had not, in that case, carried out experimental work was true; but if that work had already been done, and in the case of the wires done well, they failed to see the necessity of wasting time repeating the results which had been obtained. Mention was made of the possibility of grain-growth after stressing the steel to the yield point and then annealing it. Was Professor Edwards quite sure that in a steel with apparently fully 0·2 per cent. carbon that the conditions specified did produce marked growth? The conditions were clearly very widely different from those which obtained in his own work with Mr. Pfeil, and it should be very definitely recognised that the carbon affected the growth markedly. It was also of interest that Unwin himself said that after the straining and annealing the steel "is completely restored to the condition before overstraining." Professor Edwards appeared to have overlooked the difference between steel and his iron specimens with respect to the treatment. The remarks made about the inconsistencies of the results on Unwin's wires and Dalby's tests lose all their weight when impartially reviewed. It was true that they were by no means so regular as were the figures for the wires in Table II. No special precautions, however, were adopted in the tests, and the variations certainly did not much exceed the probable experimental error. Broadly, both sets of results agreed with the authors' hypothesis. The results given for rails of different sections were also criticised by the speaker. It was quite true that the carbon contents varied in the same direction as the values for the elastic limit. The authors doubted, however, whether on more mature consideration Professor Edwards would still seriously suggest that a variation of, in the limiting cases, 0·04 per cent. carbon was responsible for a difference of elastic limit of nearly 5 tons per square inch. He was mistaken in the statement that Unwin gave figures for either the phosphorus or the manganese content. Professor Edwards appeared to have obtained that erroneous idea from another table on the same page which had no relation to the figures quoted by the authors. The authors took the most serious exception to the statement of Professor Edwards that the figures for the plates were not accurately recorded. There were many factors which might lower the yield point considerably— inclusions, overannealing, excentric loading in the test, scratches on the specimen, &c. The chances of obtaining a yield point on the high side were, however, much smaller, and the maximum values given by Unwin were far more likely to give the true results than others. Lest Professor Edwards' remarks should lead others to believe that the authors had deliberately attempted to deceive readers of the paper—and it was difficult to imagine what other interpretation the remarks made could have—the figures as recorded were given below :

Thickness in inches .	0·12-0·13	0·13	0·14-0·2	0·18-0·2	0·23-0·30
Yield point (tons per square inch) .	15·7-16·6	14-24	17-23	25-31	16·4-19·3.
Mean . . . . .	16·2	17·9	19	20	28



Whether the maximum figures were taken, as the authors did, or the mean values given above, or the minimum ones, the variation of the results was still in the same direction.

With regard to the figures in Table II., the authors had already pointed out that the regularity of the results was itself a disproof of the attitude adopted by Professor Edwards. It might modify his conclusions in that matter if they mentioned that each figure given in Table II. was the mean of six tests, each on a separate coil of wire, each set of coils being annealed separately for experimental purposes. For the elastic limit the extreme variation found for the six coils was only half a ton, and in the average the error could not possibly reach that value. The elastic limit, however, had fallen 4 tons. It was also suggested in Professor Edwards' remarks, and by Dr. Hatfield, that decarburisation was responsible for the variation. The authors' word would have to be taken that that was not the case, but quite apart from that it would be of interest to know how either speaker was prepared to reconcile his suggestion with the fact that the maximum stress was constant throughout within the limit of experimental error. If decarburisation, which reduced the tensile strength from the first to the last wire only 0.4 ton per square inch, reduced the elastic limit 3.4 tons and the yield point 4 tons per square inch, that even would be of itself proof of the enormous importance of the surface on elastic failure. Further consideration of the results would, they felt sure, cause Professor Edwards to modify his views considerably.

What Professor Edwards meant when he asked the authors to make "a tentative calculation of the influence of surface crystals," the authors were unaware. So far neither they nor anyone else were in a position to do that, and they would be glad if Professor Edwards could tell them how to do it. What the temperature of annealing of the crystals of aluminium and iron had to do with the question as to the difference of the behaviour of the two metals, they also were unable to see. That the two metals did behave differently was clear from the published photographs, and the authors would leave the question for anyone sufficiently interested to consider for themselves. Finally, they would point out that they were still unaware whether Professor Edwards agreed with their hypothesis or not. His criticisms dealt with only one portion of the facts produced and there did nothing to disprove them. Assuming that he was not in agreement, the authors would suggest that he read the paper by Merrils in the last *Carnegie Memoirs*, where conclusions identical with those of the authors had been reached independently and from purely experimental considerations.

Mr. Evans was in, at any rate, partial agreement with the hypothesis dealt with in the paper, and the authors were glad of the contribution. Whether their own or Mr. Evans' explanation of the phenomenon was the correct one would have to remain for the moment unsettled.

## Iron and Steel Institute.

### FERROUS ALLOYS RESEARCH.

PART I.—Introduction. By WALTER ROSENHAIN, D.Sc., F.R.S.  
(National Physical Laboratory).

PART II.—Iron and Oxygen. By FRED. S. TRITTON and D. HANSON,  
D.Sc. (National Physical Laboratory).

PART III.—The Estimation of Oxygen in Pure Iron. By T. E. ROONEY,  
A.I.C., A.M.S.T. (National Physical Laboratory).

#### PART I.—INTRODUCTION.

By WALTER ROSENHAIN, D.Sc., F.R.S.

THE present paper contains the first results of a research on the alloys of iron which was commenced rather more than a year ago, under the auspices of the newly formed Ferrous Alloys Research Committee. For a considerable period of years, dating from 1890 to 1921, the Alloys Research Committee of the Institution of Mechanical Engineers was responsible for the conduct of a long series of important metallurgical investigations. While some of the Reports to that Committee dealt with iron and steel, the tendency of its activities during more recent years has lain strongly in the direction of non-ferrous alloys, and particularly of alloys of aluminium. With the publication of the Eleventh Report in 1921, however, it was felt that while finality could not be reached in research of this kind, a definite stage had been attained: consequently, it seemed desirable to devote future attention to the study of other metals. It was suggested by the present writer, and the suggestion was warmly approved by the Alloys Research Committee, that the study of the alloys of iron was now of particular importance. In the case of the alloys of aluminium, results of considerable value had been obtained, principally by means of the detailed study of the constitution of a number of complex alloy systems, developed from the previous study of the simpler alloys. Although a very large amount of research work has been devoted to the study of the alloys of iron in the form of steel, it seems that a satisfactory foundation for a full knowledge of the constitution of the alloys of iron itself is still lacking, mainly

because the actual alloy steels which have been studied contain a varying amount of carbon, which exerts so profound an influence upon them that a knowledge of the simple binary alloys of iron and other elements in the absence of carbon has still to be obtained. It may confidently be anticipated that the study of the constitution, structure, and properties of binary alloys of iron with other elements, in the first place in the absence of carbon, will yield important results. Such results may be looked for in many different directions. Some of the binary alloys themselves, free from carbon, may prove to have exceptionally valuable properties which would be discovered, since the physical properties of the alloys are to be studied as far as possible at the same time as their constitution and structure. The central fact, however, is that a knowledge of the constitution of the binary alloys of iron in the absence of carbon is necessary as a foundation for a satisfactory knowledge of the ternary and quaternary alloy systems, which include all the well-known alloy steels, and no doubt cover a whole range of other steel alloys whose properties yet remain to be discovered. This great field has hitherto been explored mainly by methods of trial and error, with the result that although a number of most important materials have been developed, it is unlikely that the possibilities have been exhausted. For example, the recent production in America of a magnetic alloy of remarkable properties in the iron-nickel series (Permalloy) shows how much yet remains to be discovered. Fundamentally, the difficulties which beset an understanding of the constitution of alloy steels arise from the fact that the presence of carbon complicates their behaviour to such an extent that a complete study of the ternary equilibria is necessary. As a basis for this study the thorough exploration of the binary alloys of iron with the more important elements, such as nickel, chromium, manganese, &c., and also with oxygen, is essential.

A programme of investigation of the kind indicated is obviously very wide and abounds with experimental difficulties, which arise from the high temperatures involved in the production of iron alloys and from the ease with which the alloys are contaminated either by oxygen or carbon, or both. The production of pure iron alloys in the Laboratory, in quantities sufficiently large to allow of the study of physical properties as well as constitution, implies the

initiation of a research on a scale at least as large as that on which the investigations of aluminium alloys have in recent years been carried out at the National Physical Laboratory.

In order to make it possible to carry out a programme of this kind, involving a large annual expenditure continued over a considerable number of years, Sir John Dewrance, K.B.E., then acting as Chairman of the Alloys Research Committee, brought about the formation of a new Committee called the Ferrous Alloys Research Committee which, unlike the old Committee, is not connected with any one society or institution, but is composed of representatives of a number of the leading scientific and technical societies and institutions, including the Royal Society, the Institution of Civil Engineers, the Institution of Mechanical Engineers, the Institution of Naval Architects, the Institution of Electrical Engineers, the Iron and Steel Institute, and the Institution of Mining and Metallurgy. Under the auspices of this Committee, and with the concurrence of the Advisory Council of the Department of Scientific and Industrial Research, a beginning has been made upon the programme of Ferrous Alloys Research, but not as yet on the full scale that is desirable. Thus, the physical tests on iron and iron-oxygen alloys described below in the attached paper by Tritton and Hanson have of necessity been carried out on unduly small samples, owing to the great cost in time and money which would have been involved in the production of these materials in larger quantities.

It is, perhaps, desirable to indicate the nature of the work involved in a research of this kind, in order to explain the requirements in experimental equipment and trained workers essential for its satisfactory progress. A preliminary step in the study of these alloys is the provision of materials of the highest purity. Iron itself must be obtained free from all measurable admixtures, and the same applies to the alloying elements, such as chromium, manganese, &c. It has proved impossible to obtain them commercially, and their preparation in the Laboratory has had to be undertaken. As considerable quantities are required, this has already occupied much time and equipment: in some cases the methods of producing the pure metal have themselves involved a lengthy and difficult research, for which special apparatus has had to be developed and constructed.



The melting of such pure metals and their alloys, so as to avoid contamination by traces of carbon, has also proved a matter requiring prolonged experimental work. During the earlier stages of the investigation the best furnaces available were the "graphite-ring" type of electric resistance furnace which has been developed at the National Physical Laboratory, and in these it was essential to evolve a type of refractory muffle which would protect the molten metals from carbon at temperatures near 1600° C. The use of these furnaces and of such methods of protection is still essential for obtaining high-temperature thermal curves of the alloys. More recently, the work has been much facilitated by the use of the Ajax-Northrup high-frequency induction furnace. Even with this apparatus, which is a costly item of laboratory equipment, considerable difficulties have had to be overcome, while the quantity of iron alloy which can be melted, in the total absence of carbon, in the 25 K.V.A. size of furnace is much too small to allow of satisfactory physical testing.

A further series of fundamental difficulties arises from the high temperatures used and the great chemical activity of the molten metals and their vapours. Special methods of protecting thermocouples and of preparing highly refractory and resistant crucibles have had to be developed. Some reference to these is made in the attached paper, while a fuller account of the methods of producing crucibles is to be published elsewhere by Tritton.

The efficient conduct of a research of this magnitude requires, in addition to extensive experimental equipment, the services of a considerable staff of trained research workers and of subsidiary assistants. A number of alloy systems can be most satisfactorily studied simultaneously, since such an arrangement makes progress possible at a reasonable rate and allows expensive apparatus to be more continuously used. It has the further advantage that many difficulties common to various alloy systems can be simultaneously attacked and overcome. In this connection it is desirable to point out that the present research, while it is being carried out under the immediate personal direction of the writer, is the work of an organised team of research workers, including metallurgists and chemists, who work in the closest possible co-operation. Further, much important help is also given by



members of the staff of other Departments of the National Physical Laboratory. The Physics, Electrical, and Engineering Departments may be particularly mentioned.

Some difficulty arises in regard to the authorship of papers representing the results of collaborative work of this kind ; in the present case the results will be published, when approved by the Ferrous Alloys Research Committee, in the form of a series of papers in the names of the research workers who have been mainly concerned with that particular portion of the work. A general heading and, when required, introductory remarks will, however, serve to preserve the continuity of the whole series of researches and to indicate the present author's responsibility for the research as a whole.

## PART II.—IRON AND OXYGEN.

By FRED. S. TRITTON and D. HANSON, D.Sc.  
(National Physical Laboratory).

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## INTRODUCTION.

THE effect of oxygen on iron has been investigated by a number of workers, the most recent publications on the subject being by

Picard,<sup>1</sup> Stead,<sup>2</sup> Whiteley,<sup>3</sup> and others. The work of these investigators has partly been concerned with methods of estimating the amount of oxygen in iron, and partly with the solubility of oxygen in solid iron and its effect on the etching of iron with cupric reagents. The present research has for its object the determination of the constitution of the iron-oxygen alloys, and the effect of oxygen and iron oxide on the mechanical and physical properties of iron.

### MATERIALS.

*Iron.*—The purest iron readily available in reasonable quantities at the commencement of the research was commercial Armco iron, the average analysis of which was found to be as follows :

	Per Cent.
Carbon . . . . .	0·015
Silicon . . . . .	0·015
Sulphur . . . . .	0·02
Phosphorus . . . . .	0·015
Manganese . . . . .	0·07

This was used in some preliminary work, but later the material was found to be unsuitable, and arrangements were made for the production of electrolytic iron in the necessary quantities at the Laboratory.

For this purpose a chloride bath was preferred to a sulphate bath, since it is impossible to remove all traces of electrolyte from the deposited metal by washing; on remelting, however, any chloride residue would be evaporated, whereas sulphate residue would probably react with iron and leave traces of sulphide in the metal.

The method of Cain, Schramm and Cleaves<sup>4</sup> was used. The electrolyte consisted of a solution containing 288 grammes of pure ferrous chloride and 57 grammes of pure sodium chloride per litre of water. Armco iron anodes were employed, with a current

<sup>1</sup> "The Oxygen Content of Iron and Steel," *Iron and Steel Institute : Carnegie Memoirs*, 1916, vol. vii.

<sup>2</sup> "Solid Solution of Oxygen in Iron," *Journal of the Iron and Steel Institute*, 1921, No. I. p. 271.

<sup>3</sup> "Cupric Etching Effects produced by Phosphorus and Oxygen in Iron," *Journal of the Iron and Steel Institute, Ibid.*, p. 277.

<sup>4</sup> *Bulletin of Bureau of Standards*, 1916-17, vol. xiii.

density of 0.6 ampere per square decimetre, the solution being used cold.

The average chemical analysis of this material as deposited is as follows :

Carbon	.	.	.	.	.	.	trace
Silicon	.	.	.	.	.	.	nil
Sulphur	.	.	.	.	.	.	nil
Phosphorus	.	.	.	.	.	.	nil
Manganese	.	.	.	.	.	.	nil

The oxygen content of clean-looking pieces of electrolytic iron in cathode form was found to be 0.277 per cent.

This appeared to be due to the formation of rust in the iron, which was deposited in a slightly porous form. It was not found possible to prevent rusting, although the greatest care was taken in drying the material. The presence of this oxide was a great source of trouble in obtaining melts of iron free from oxide. The oxygen was estimated by the usual methods, but with special refinements, a description of which will be published elsewhere.

*Iron Oxide.*—For preliminary work iron oxide was obtained by passing oxygen over red-hot turnings of Armco iron until they were completely oxidised, but the preparation was tedious and the results were found to be not always uniform ; attention was therefore turned to other sources of supply. It was found that ferric oxide of sufficient purity could be obtained from Messrs. Canning of Birmingham, whose quality "AA" was found to contain only the following impurities :

							Per Cent.
Silicon	.	.	.	.	.	.	0.16
Sulphur	.	.	.	.	.	.	0.044
Phosphorus	.	.	.	.	.	.	trace

This material was used in most of the work here recorded.

*Pots and other Refractories.*—One of the greatest difficulties of this research was to obtain pots and other refractory articles suitable for the work. The only pots of suitable size that could be obtained, after searching inquiry, were made of either silica, china clay, or alundum, in none of which was it found possible to hold molten iron containing much oxide for more than a few minutes, owing to the rapid attack on the pot by the oxide. A very small supply of magnesia pots of German manufacture was soon exhausted and could not be replaced. The manufacture of pots in the Laboratory was therefore attempted, and after con-

siderable experiment the technique of the manufacture of pots and tubing of most of the refractories has been acquired, and has now become part of the routine work of the Laboratory. This knowledge of the manufacture of highly refractory articles of great purity is a valuable result of the present researches in ferrous alloys, and will be of great assistance in the future work.

The usual methods of manufacture of pots by bonding together previously shrunk refractory material proved inadequate in certain circumstances. A new method has been developed for producing pots having internally glazed surfaces, of great resistance to chemical attack, by means of direct fusion of the refractory in an electric arc. The refractory, which must have been previously melted and powdered, is placed in a suitable receptacle and spun under an electric arc in such a way as to form in a few minutes a well-shaped pot having a body of highly fired material, the internal surface of which has been completely molten, leaving a glazed surface on the interior of the pot. Pots produced in this way proved after trial of every suitable refractory material, the only kind able to hold molten iron and iron-oxide at the same time.

A full description of this new method, the further development of which may prove important, will be published elsewhere.

### PREPARATION OF ALLOYS.

*Early Work.*—During the early part of this work all melting of alloys and heating for high-temperature thermal curves was done in a 4-inch diameter carbon-ring furnace.<sup>1</sup> To prevent the contamination of the melt with carbon, an almost gas-tight refractory muffle was necessary, which reduced the available pot space to a diameter of about  $1\frac{3}{4}$  inch. Pots had therefore to be of certain rather strict dimensions in order to give melts of sufficient weight for thermal curves, microscopic examination, and chemical analysis. The most convenient melt was found to be one of 50 grammes weight. Later a high-frequency induction furnace (Ajax-Northrup) was available, and proved an invaluable help by making possible the melting of iron *in vacuo* or hydrogen, which could not be done in the carbon-ring furnace.

A series of cooling curves was first taken, starting from pure

<sup>1</sup> Rosenhain and Coad-Pryor, *Transactions of the Faraday Society*, 1918.



iron and going on to alloys of iron having increasing quantities of oxide. These cooling curves were taken from above the melting point of iron down to about  $640^{\circ}\text{C}$ . Armco iron was melted in an atmosphere of nitrogen, as pure as it could be maintained under the existing conditions, which are not very favourable, as the top of the muffle could not be kept gas-tight, owing to the necessity of introducing the thermocouple, &c., at high temperatures, and to occasional leakage of gas through the walls of the muffle when very hot.

For low-oxygen melts china-clay pots were used, while for higher-oxygen contents bonded pots of fused magnesia were employed. Pots of alumina, alundum, chromite, zirconia, and lime were made and tried, but were found to crack and disintegrate with melts having a high-oxygen content. Magnesia pots absorbed oxide but seldom cracked, even when saturated right through. These pots were made from fused magnesia obtained in lump form from America. The material was first crushed, ground, and treated magnetically to remove iron, then damped with water and moulded into pots, which were finally fired to about  $1560^{\circ}\text{C}$ . in a kiln. Owing to the restricted size of the pot, it was not feasible to line silica pots with alumina and magnesia as might be possible in the case of larger crucibles or the open hearth of a furnace.

*Thermocouples and Cooling Curves.*—All the thermocouples used in the research were calibrated against the Laboratory standard couples up to  $1300^{\circ}\text{C}$ . The values above this are based on extrapolation, assuming the palladium point to be  $1549^{\circ}\text{C}$ . Occasionally the E.M.F. of the couples was also obtained at the melting points of gold and palladium and by inter-comparison with a standard optical pyrometer over a range of  $1100^{\circ}\text{C}$ . to  $1500^{\circ}\text{C}$ . The melting point of iron obtained under certain conditions was found to be a useful check.

A platinum-platinum-rhodium thermocouple was used, protected by a refractory tube, made by extruding a mixture of china clay and 10 per cent. of alumina in a wet plastic state and subsequently firing to  $1560^{\circ}\text{C}$ . Where magnesia pots were used it was found necessary to coat the bottom of the couple protector with alumina to prevent reaction between the protector and the bottom of the pot, which at first was a source of trouble and failure. The procedure in taking a cooling curve was to melt the iron, then add

a known quantity of oxide by dropping in small briquettes of ferric oxide powder. The thermocouple was then inserted into the metal and the furnace current manipulated so as to cool the furnace down in a uniform manner. The melt was inoculated by dropping iron sawdust into the melt over the freezing range to prevent under-cooling, which otherwise became a source of error. The time factor for the penetration of the couple sheath by the oxide was about two minutes, so that unless the couple was put into the metal at just the right temperature, so that it cooled down and solidified in approximately this time, the couple protector was drilled and couple and curve were spoilt. Curves were taken on the Rosenhain plotting chronograph.

By these means a series of six cooling curves was obtained on ingots having oxygen contents varying from 0.08 to 0.21 per cent. oxygen, but the freezing and other points were found to vary over 25° C. without any apparent relation to the oxygen content. It was therefore obvious that couple contamination was a source of error to a degree not hitherto suspected.

Microscopic examination of these ingots showed that the small oxide globules in the metal had a duplex structure, this being the result of the combination of the oxide with the impurities of the iron. Arrangements were therefore made, as already mentioned, for the production of electrolytic iron of much greater purity.

The couple contamination testing device illustrated in Fig. 1 was made, and proved useful in the constant checking of the contamination of the couple. This checking was later made part of the daily routine. Work was continued on these lines, using every effort to discover the cause of couple contamination, which appeared to fluctuate without obvious reason.

The testing device consists of two water-cooled clamps 2 feet apart, between which the wire to be tested was stretched. A small flat coal-gas flame produced by an acetylene burner mounted on a moving carriage traversed the length of the wire. The ends of the wire to be tested were connected with a galvanometer. The flame produced a steep temperature gradient, varying from 900° C. to 15° C. in an inch length of wire, which, if contaminated, generated a small current and caused a deflection of the galvanometer. Readings were taken over the whole length of the wire, moving the flame 1 inch or  $\frac{1}{2}$  an inch at a time. Contamination

that would cause a difference of  $1^{\circ}$  C. at the melting point of iron in the carbon-ring furnace would give a galvanometer deflection under test of about 30 microvolts, owing to the very steep temperature gradient produced by the flame.

It was then found that the shape of the pot holding the metal appeared to influence the amount of contamination. The pot first used was  $2\frac{1}{2}$  inches high and  $\frac{7}{8}$  inch in diameter, and is illustrated in Fig. 2 (a). The pot was made with high walls, so that

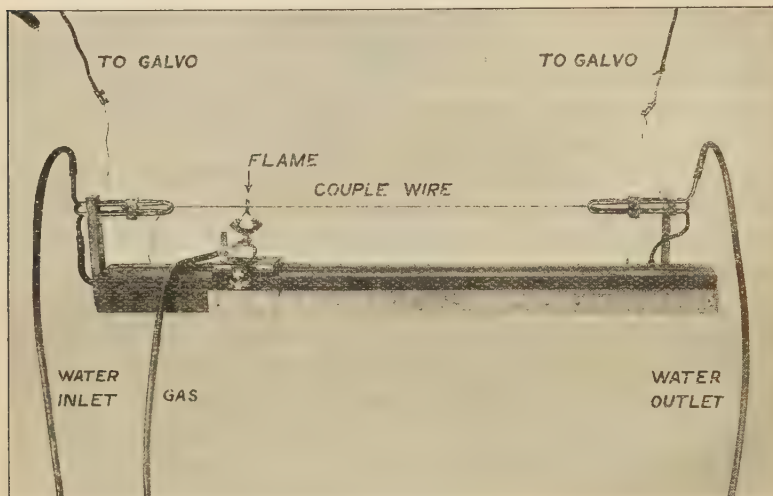


FIG. 1.

the whole charge (50 grammes of electrolytic iron) could be easily introduced at once ; adding metal at high temperatures to small melts was often found to lead to disaster. In order to prove that the shape of the pot was of importance, iron was first melted down in the high pot to a compact ingot approximately  $\frac{5}{8}$  inch by  $\frac{7}{8}$  inch without taking a cooling curve ; the top of the pot was cut off to within  $\frac{1}{8}$  inch of the top of the melt and the ingot remelted in the same pot and a cooling curve taken. This at once effected a great improvement in couple contamination, which appeared to be caused by the iron vapour penetrating the couple protector ; the tall pots greatly assisting in keeping the vapour closely around the protector and causing contamination.

Using a very low-sided pot the vapour was more easily dispersed by convection currents, and this was finally assisted by blowing a supply of nitrogen from a separate tube across the surface of the melt. Conical-shaped pots, as illustrated in Fig. 2 (b), were then made and used, so that the entire charge could be piled up above the top of the pot with comparative safety, thus saving the time required for the double melting described.

*Cooling Curves from 1530° C.*—With these improvements a

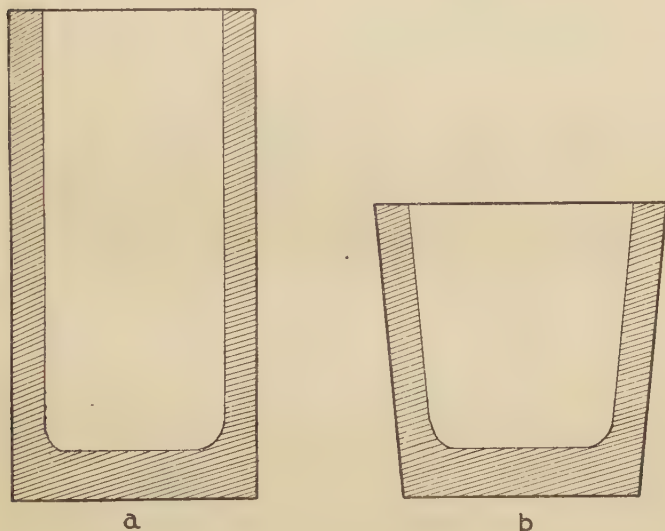


FIG. 2.

new series of cooling curves was taken on a fresh series of alloys made up in the same way as the previous ones, using electrolytic instead of Armco iron. A selection of results from these curves are given in Table I. and illustrate the type of accuracy now obtained.

Contamination was always found to be worse in the pure platinum wire of the normal 10 per cent. platinum-rhodium couple and in the part of the wire adjacent to the melt, which suggested that if a wire containing a little rhodium could be substituted for the pure platinum wire an improvement would result. This was done, and some wires containing 5 and 20 per cent. rhodium were

prepared by Messrs. Johnson, Matthey & Co., Ltd. These wires gave an E.M.F. of 9930 microvolts at 1530° C. and 3050 microvolts at 763° C., and were found to be far less sensitive to contamination than the usual platinum and 10 per cent. platinum-rhodium couple.

TABLE I.  
*Liquidus Point.*

Melt No.	Oxygen (by Analysis) per Cent.	Observed Commencement of Solidification, Deg. C.	Beginning of Arrest Point on Curve, Deg. C.	Curve Peak, Deg. C.	Delta Point Ar4, Deg. C.	Gamma Point Ar3, Deg. C.	Beta Point Ar2, Deg. C.
C10	0.1	1529	1529	1526	1408	845	764
D1	0.12	1524	1525	1511	1394	847	759
C12	0.15	1525	1526	1522	1394	865	764
E5	0.18	1526	1526	1519	1394	861	759
E6	0.21	1519	1519	1509	1376	861	751

*A3 and A2 Arrest Points, obtained by reheating in vacuo.*

Melt No.	Oxygen (by Analysis) per Cent.	Heating Curve.		Cooling Curve.	
		Ac2.	Ac3.	Ar3.	Ar2.
D1	0.12	763	912	885	763
D3	0.15	767	912	885	763
D6	0.21	763	912	889	763

A reproduction of a cooling curve of iron from 1550° to 600° C. obtained with this couple is shown in Fig. 6 (A), and illustrates the type of arrests obtained. \*

These three improvements—viz. low-walled pot, 5/20 per cent. rhodium couple, and blowing nitrogen across the top of the melt—practically removed the trouble of bad couple contamination. Although a small amount of contamination was always present, it could now be closely followed by the testing apparatus and the contaminated portion of wire removed after it had passed a certain limit. In order to illustrate the amount of contamination obtained when using the improved methods, a number of curves are shown in Fig. 3, illustrating the amount of contamination obtained in a 5/20 per cent. platinum-rhodium couple after taking successive



cooling curves from  $1540^{\circ}\text{C}$ . It will be seen that the contamination is slowly progressive, but can be watched with confidence by testing after each curve.

In order to test the constancy of the couple a series of cooling

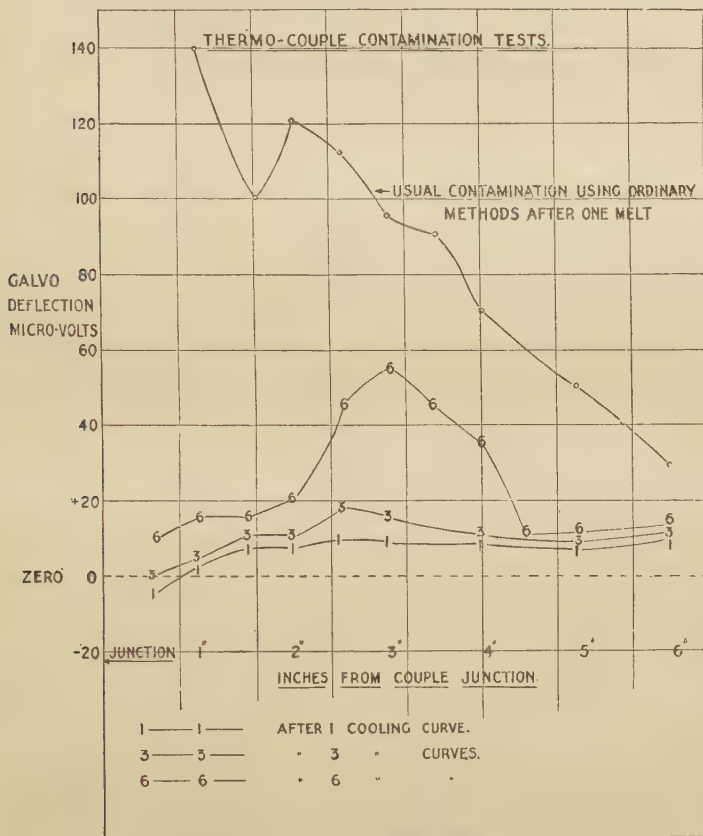


FIG. 3.

curves of pure electrolytic iron in an atmosphere of nitrogen was taken in succession in exactly the same way, and the observed commencement of freezing was found to agree to within  $0.2^{\circ}\text{C}$ . in three successive melts, showing that with great care considerable accuracy can be obtained at these temperatures.

*Freezing Point of Iron.*—The freezing point of iron, determined

as indicated above, was found to be  $1530^{\circ}\text{C.}$ , assuming a melting point of  $1549^{\circ}\text{C.}$  for palladium. Recent work at the Bureau of Standards gives a melting point of  $1555^{\circ}\text{C.}$  for palladium, and the melting point of iron, referred to this latter standard, is  $1535^{\circ}\text{C.}$

This freezing point was redetermined by melting electrolytic iron in an atmosphere of argon, in order to eliminate any effect due to nitrogen. The same freezing point was obtained. The transformation points of solid iron were also unaffected.

This is probably a very close approach to the freezing point of pure iron, but the presence of about 0.1 per cent. of oxygen must be remembered. The slight slope of the liquidus curve of the iron-iron-oxide diagram (see Fig. 8), however, suggests that the effect of this amount of oxygen must be small.

*Lower Critical Points.*—In order to ascertain the effect of oxide on the lower critical points of iron more accurately than was possible with curves taken from the melting point, a series of curves was obtained, using the usual heat gradient furnace, Rosenhain plotting chronograph, and taking the curves of the samples *in vacuo*.

The results, which are given in Table I., show no variation of these arrests with varying oxide content.

It was not found possible to obtain alloys having less than 0.09 per cent. or more than 0.21 per cent. oxygen by the methods then available, as no furnace muffle could be obtained that was sufficiently gas-tight to allow the employment of hydrogen or a vacuum at these temperatures. The results of the curves in Table I. show that the effect of oxide content on the freezing points of these alloys was very small, an increase in the oxygen content from 0.1 to 0.2 per cent. causing a drop of not more than  $10^{\circ}\text{C.}$  in the liquidus. The difficulties of obtaining iron completely free from oxide appeared to be great, and attention was directed to obtaining alloys of higher oxygen content in order to find the saturation points.

*Maximum Solubility of Oxide in Iron.*—The addition of more oxide to the melt produced no result, as the oxide merely ran out through the pores of the pot. Having thoroughly tried, without success, many devices to hold the oxide, including the successful making of pots partly composed of iron-oxide, in order that they might start saturated with oxide, it was decided to conduct experi-

ments with a view to obtaining a pot having a glazed surface through which the oxide could not penetrate. The experiments were quickly successful, and the pots described in the "Materials" section of the paper were obtained. One or two of these pots were found to hold the liquid oxide at  $1540^{\circ}\text{C}$ . without any leakage, with the result that two liquid layers were found, as suspected, and maximum saturation obtained. The method of melting was as follows :

A pot was partly filled with oxide (which had been previously melted in a pot made of Armco iron to reduce volume), with an upright piece of electrolytic iron in the centre to act as a "sentinel," to show when the iron was melted. The oxide melted first, and when the iron sentinel fell and the charge was quiet in the pot the furnace was cooled down, the iron having been molten about two minutes.

The weight of the most successful melt was  $8\frac{1}{2}$  grammes, giving about 3 grammes of iron and 5 grammes of oxide for analysis. Other melts were obtained, but in many cases the oxide ran out of minute pinholes which developed at the intersections of fine cracks in the glaze of the pot. So far it has not been possible to produce a pot of magnesia which has not a few cracks in the glaze.

Analysis of the two layers in these melts when separated gave the following results :

	Per Cent.
Oxygen in the iron layer . . . .	0.21
Free iron in the oxide layer . . . .	0.99
FeO " " " " . . . .	80.6
Fe <sub>2</sub> O <sub>3</sub> " " " " . . . .	14.0
SiO <sub>2</sub> " " " " . . . .	0.40
MgO " " " " . . . .	3.0

The oxygen content of the iron agrees well with the previous highest figure of 0.21 per cent. oxygen obtained with the bonded pots, and appears to be the correct figure for the maximum solubility of oxygen in iron at a temperature of about  $1530^{\circ}\text{C}$ .

*Melting Point of the Oxide.*—The determination of the melting point of the oxide was next attempted. First, ferric oxide was melted in an Armco iron pot and the temperature measured by means of a thermocouple in a china-clay tube, sheathed again in a thin tube of Armco iron. After repeated failures, due to the extreme weakness of the Armco sheath and its tendency to weld to

the pot at such high temperatures, a fairly successful heating and cooling curve was obtained, giving the following arrests :

Arrest on heating	:	:	:	:	:	1362° C.
Arrest on cooling	:	:	:	:	:	1366° C.

A second attempt was made, using a platinum thimble and fixing the bare couple into a central position in the pot, the pot

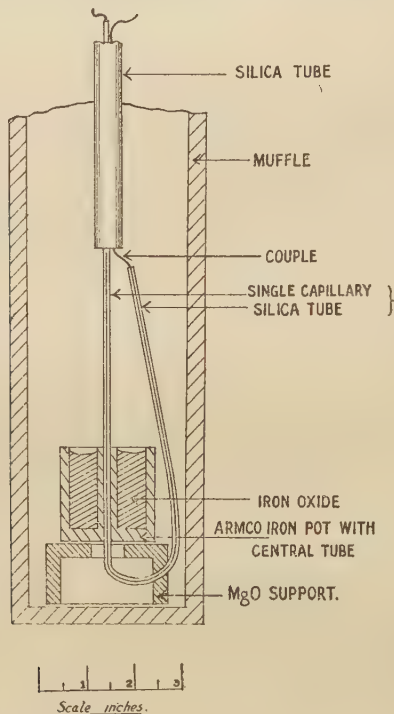


FIG. 4.

being filled with oxide which had been previously melted. It was thought that this would give at any rate an accurate melting point before the couple became contaminated. The only result that was considered to be worth recording was the first point on heating, which occurred at 1376° C. Three heating and cooling curves were taken in succession by this method, but the results after once melting the oxide were useless, owing to couple contamination.

Finally, a reliable heating and cooling curve was obtained, using the arrangement shown in Fig. 4. The thermocouple was passed

through a fine silica tube which fitted into the iron tube in the centre of the pot, and when in position the silica tube was carefully bent in a flame completely round, as shown. The silica bends at  $1300^{\circ}\text{C}.$ , and no harm was done to the couple inside. This arrangement reduced the heat insulation of the couple to a minimum, and at the same time completely protected the couple from the oxide for a short time and from contaminating vapours in the hottest zone. These curves gave the following results :

Arrest on heating	:	:	:	:	$1371^{\circ}\text{C}.$
Arrest on cooling	:	:	:	:	$1369^{\circ}\text{C}.$

A reproduction of one of these curves is given in Fig. 6 (D). As this result appeared to be accurate, it followed that the globules of oxide in the saturated iron were still liquid at  $150^{\circ}\text{C}.$  below the freezing point of iron, and should give an arrest that had not previously been noticed. The close proximity of this point to the delta point of iron at  $1400^{\circ}\text{C}.$  was of interest, and it was clear that the two should be separated if possible. Using the arrangement shown in Fig. 4, a great source of difficulty was the rapid attack on the silica tube by the oxide continually forming in the iron tube when this was above the melting point of the oxide, but it was found that there was just time to heat above the melting point and cool down again before the silica tube was penetrated. All these curves were taken in muffles open to the air, but excessive oxidation was prevented by passing some nitrogen into the muffle.

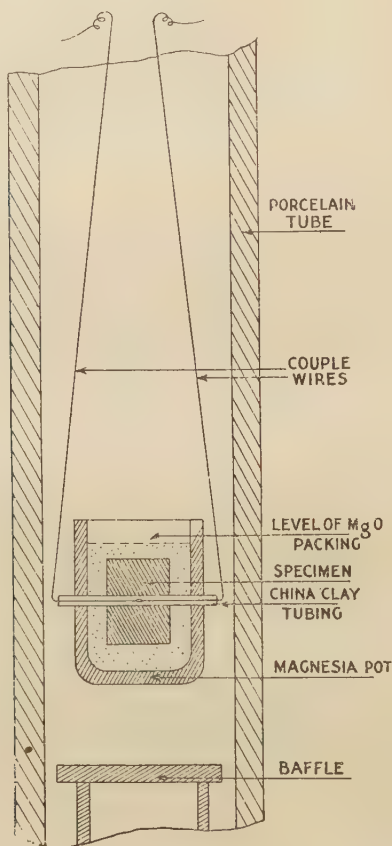
*Delta and Oxide Arrest Points.*—Efforts were now made to secure the arrest due to the solidification of the oxide particles in iron containing 0·1 per cent. to 0·2 per cent. of oxygen. It was obvious

Melt No.	Oxygen Content by Analysis. Per Cent.	Heating Curve.		Cooling Curve.	
		Oxide.	Delta Point.	Delta Point.	Oxide.
D20	0·1	1371	1407	1396	Not definite
D24	0·21	1376	1407	1396	Not definite

that with so small an amount of oxide present the arrest would be very small, and couple protection must be reduced to a minimum in order to observe it. After a number of fruitless attempts by various methods, the method illustrated in Fig. 5 was found to be



successful and the following arrests were obtained, that due to the oxide being very small but distinct on heating. The cooling curves were not so good.



Full Size.

FIG. 5.

The heating and cooling of the tube containing the specimen was done by altering the electric current of the carbon-ring furnace at a uniform rate, no heat gradient furnace for these temperatures being available. The production of a uniform rate of heating and cooling smooth enough for the detection of such small thermal arrests was not easy.

Some typical heating and cooling curves showing the variation in size of the oxide and delta arrests of iron with the amount of oxide present are shown in Fig. 6. Curve 6 (b) was obtained from iron having an oxygen content of 0.15 per cent. Curve 6 (c) from a specimen of iron in which a number of small holes had been drilled; these recesses were subsequently filled with oxide, thus artificially producing iron having a number of large oxide inclusions, which gave an arrest point that is decisive. Curve 6 (d) was obtained from iron-oxide melted in an iron pot, the small delta arrest is given by the thin iron couple sheath.

It was not considered possible to obtain a cooling curve of the two immiscible layers of iron and iron-oxide from above the melting point of iron, owing to the difficulty of protecting the thermocouple from attack.

These results indicate that the oxide constituent of the iron-rich alloys does not solidify on cooling until a temperature of about 1370° C.—a temperature which agrees well with the melting and freezing points of iron-oxide melted in an iron pot.

*Solid Solubility.*—The solid solubility of oxide in iron appeared to be very small, but it was thought that an increase was likely to occur at temperatures above the melting point of the oxide. In order to investigate this a number of specimens of iron containing 0.21 per cent. oxygen were slowly heated to various temperatures up to the melting point of iron and quenched in water. The micro-structure was afterwards examined and the amount of oxide present noted. The appearance of iron containing 0.21 per cent. of oxygen quenched from the melting point, when half liquid and half solid, is illustrated in Fig. 14 (Plate V.), at a magnification of 100 diameters. The arrangement shown in Fig. 7 was found to be satisfactory for this work. To quench the specimen, the tube A, with lid complete, was quickly lifted out of the muffle and the pot containing the specimen quenched in water. The result showed no diminution in the amount of oxide present, indicating that there was no further solubility of the oxide in the iron up to the melting point.

*Iron Free from Oxide.*—The high-frequency induction furnace being now available for use, a number of experiments were made to try and procure iron entirely free from oxide. At first electrolytic iron (previously purified by heating in hydrogen at 1200° C.) was

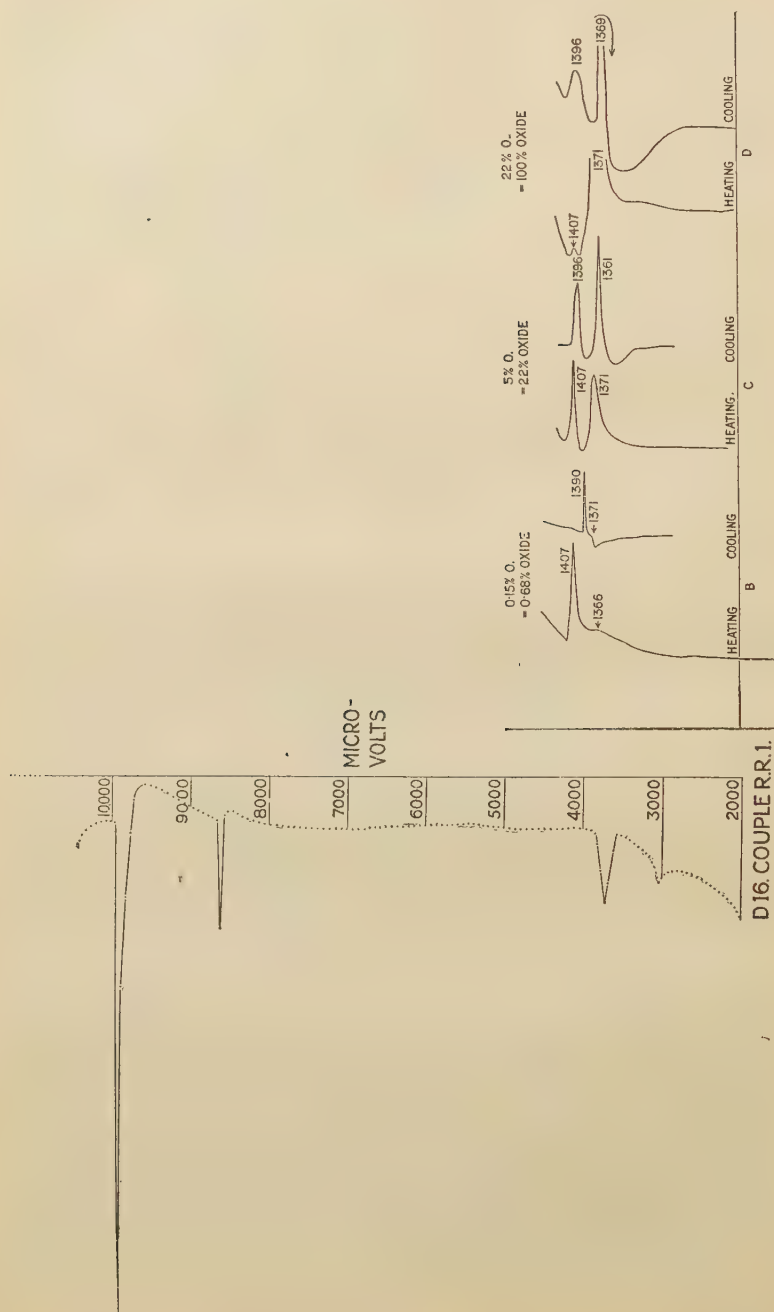


Fig. 6.

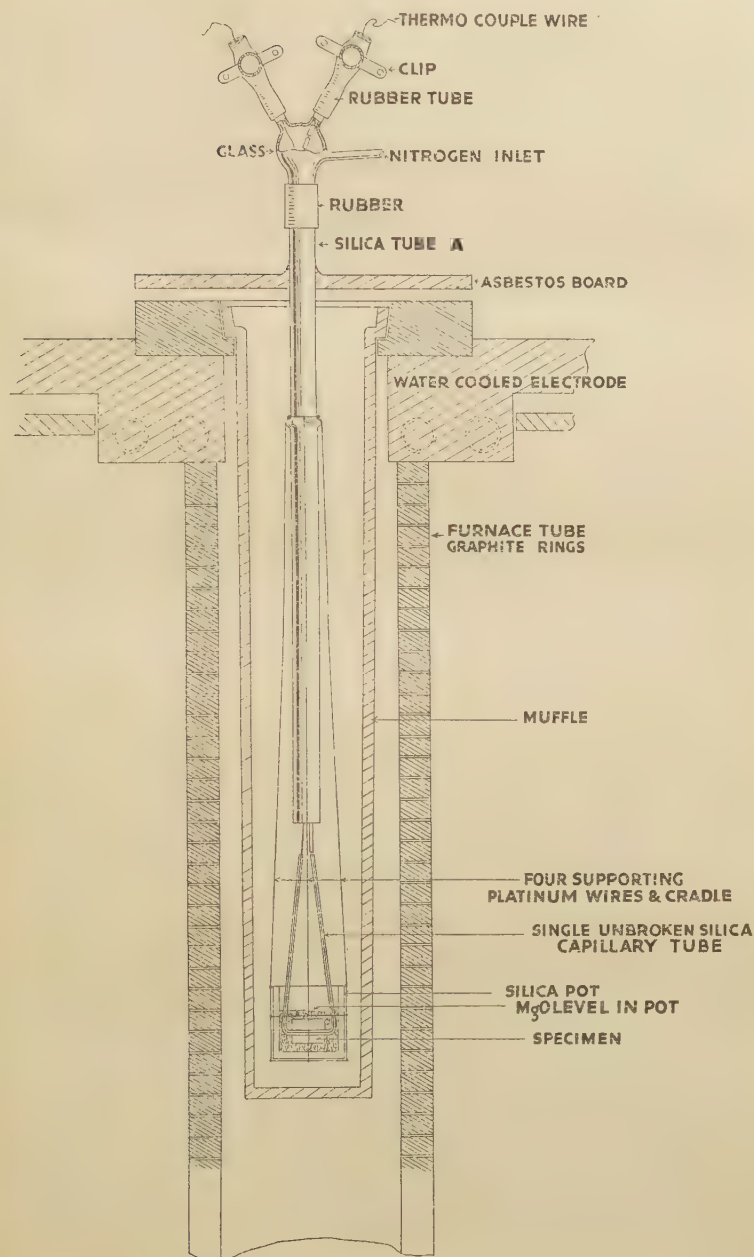


FIG. 7.

melted in a vacuum of about 2 millimetres of mercury, but the melts were not free from oxide. Then iron was melted in purified hydrogen, the hydrogen being sometimes passed through the melting tube continuously, and at other times the tube was evacuated and refilled with purified hydrogen alternately, a number of times, but with no better results. Finally, purified hydrogen was blown directly on to the surface of the metal during melting and for a period of fifteen minutes when molten, but the melt was found to contain an amount of oxide that was estimated to represent about 0.08 per cent. oxygen. Both china clay and magnesia pots were used. Although every care was taken, there appeared to be a small but continuous supply of oxygen from some source, possibly by the reduction of the constituents of the pots.

The problem of the production of iron totally free from oxide therefore appeared to be difficult, and one that might almost evolve into a fresh research: further work on this problem was therefore postponed and attention turned to the production of ingots of sufficient size to be rolled into rods, whose physical properties could be tested in the usual ways. Some of the methods used for melting iron in the induction furnace are described in the portion of the paper dealing with the physical properties of these alloys.

#### CONSTITUTIONAL DIAGRAM.

From the results so far obtained an equilibrium diagram can be drawn for iron containing from 0.1 per cent. oxygen up to approximately 22 per cent., represented by the compound  $\text{FeO}$ . This is illustrated in Fig. 8 and shows a large range of insolubility of the two components, which separate into two liquid layers when molten. The diagram is plotted on two scales with a break between, in order to illustrate the results more clearly.

The liquidus is given in the diagram by the lines AB, BC, CJ. The slight lowering of the liquidus to the point B, representing the maximum solubility of oxide in iron, is indicated by the cooling curves given in Table I. This drop probably amounts only to  $8^{\circ}$  or less, and was difficult to determine with great accuracy at that period of the research. The solidus of the diagram is given by the lines AH, HJ, and is obtained from cooling curves of both oxide-rich and iron-rich alloys, and is consistent with the results of microscopical examination of the alloys.



Evidence of the liquid immiscibility of oxide and iron beyond 0.21 per cent. oxygen was obtained from melts whose compositions are indicated by crosses on the liquidus line BC: these melts were found to have formed two distinct layers of iron and oxide when cooled fairly rapidly from a temperature of 1545° C. A section

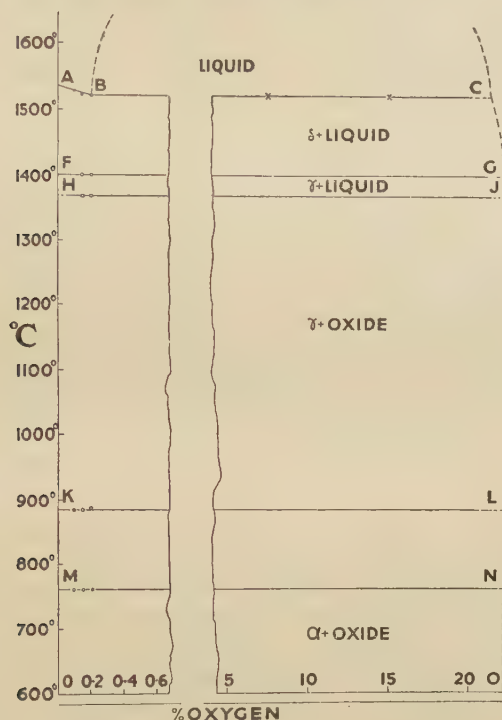


FIG. 8.

through a pot containing a melt having two layers is illustrated in Fig. 9, full size (Plate V.). The white centre is iron and the dark layer surrounding the iron at the same level is oxide. (This melt was obtained in one of the first fused magnesia pots made; later on pots of more perfect form were regularly produced, a section of one being shown in Fig. 10.)

The solid solubility of oxygen in iron has not been determined, but is estimated to be about 0.05 per cent. oxygen from the appearance of the microstructures. The amount of visible oxide

present in two samples of iron containing 0·1 per cent. and 0·23 per cent. oxygen is illustrated in photomicrographs 11 and 12 (Plate V.) respectively, at a magnification of 100 diameters. From the fairly large variation in the amount of oxide present, it seems likely that no oxide should be visible if the oxide content of photomicrograph 11 were halved. The solubility of iron in the oxide was found to be approximately 1 per cent., which is shown by the curved line CJ, and was obtained by the analysis and microscopic examination of the oxide from melts whose oxygen content is given by the two crosses on the liquidus line BC and point J. In each case the amount of free iron in the oxide layer was 1 per cent. The microstructure of the oxide is shown in Fig. 13 ; the iron can be seen as small white spots in the grain boundaries. The dotted line JO is drawn at a point representing the compound  $\text{FeO}$ , but the thermal data of the dotted lines are not accurate, as melts containing only  $\text{FeO}$  were not obtained, a small amount of  $\text{Fe}_2\text{O}_3$  being always present. The dotted part of the diagram is therefore only tentative, but at the same time the general form is probably correct. The lines FG, KL, MN, represent the delta, gamma, and beta arrest points respectively in the iron.

#### PHYSICAL PROPERTIES OF IRON CONTAINING OXYGEN.

All the material for physical tests was melted in the high-frequency induction furnace. The maximum weight of iron ingot obtainable with the present apparatus is about 450 grammes. Three ingots having a low oxygen content (about 0·08 per cent.), numbered E31, F9, F10, and three ingots having a high oxygen content (about 0·23 per cent.), numbered E24, F11, F8, were made in the following way :

*Preparation of Ingots, Analysis and Rolling.*—For low oxygen ingots the electrolytic iron was broken into small pieces of about half a square centimetre, these pieces were then annealed in a current of purified hydrogen at  $1250^\circ \text{C}$ . for four hours (*i.e.* until no further increase of weight was recorded in the moisture weighing tube) in order to remove oxide as far as possible. This metal was then briquetted in a small press to compact lumps that fitted into a pot made of pure china clay and was melted in a vacuum, which at no time was allowed to fall below 3 millimetres of mercury.

The ingots containing high oxygen were made from electrolytic iron that had not been annealed in hydrogen, but were briquetted as received from the cathode. The briquettes were melted in air in a bonded magnesia pot, and owing to the rapid swirling of the melt that is produced by the induced electrical currents, contained rather more oxide than the maximum solubility given in the equilibrium diagram. This extra amount of oxide is therefore due to mechanical entrapping of the oxide in the metal. Small ingots only were obtained in this way, owing to the shrinkage of the briquettes of electrolytic iron on melting. These small ingots were remelted, two at a time, to give larger ingots. This remelting was done *in vacuo*.

The ingots were then hot-rolled in fourteen passes to approximately  $\frac{1}{2}$  inch diameter rod, giving a reduction of cross-section of approximately 80 per cent. Before rolling, the ingot was heated in an open gas furnace to 1250° C., the temperature of the rod at the last pass being about 700° C. No cracking was observed in the rods during rolling, but exactly similar ingots of Armco iron split to pieces under the same treatment. It therefore appears that oxygen does not cause bad "hot-shortness" in iron; and, so far as the authors' experience goes, there appears to be no brittle range at high temperature in these pure iron-oxide alloys.

Attempts to cold-roll a bar of high-oxygen iron, giving a very small reduction, at once caused severe cracking, and therefore were abandoned. Further experiments in cold-rolling are described later.

The results of chemical analysis of these bars is as follows :

Bar No.	Oxygen per Cent.	Carbon per Cent.	Silicon per Cent.	Sulphur per Cent.	Phos- phorus per Cent.	Manganese per Cent.
E31 (low oxygen) .	0.08	trace	trace	trace	0.007	trace
E24 (high oxygen) .	0.23	trace	trace	trace	0.007	trace

The bars were then normalised in air in an electric resistance furnace at 1000° C., and submitted to the following tests :

*Electrical Conductivity.*—The values of conductivity given below are referred to the International Standard for annealed

copper, of which the resistance of a centimetre cube is 1.7241 microhms at 20° C.

Sample No.	Resistivity : Microhms for a Centimetre Cube.	Relative Conductivity compared with Copper of Equal Volume. Per Cent.	Temperature. Deg. C.
E31 (low oxygen) .	9.4	18.4	20
E24 (high oxygen) .	9.6	18.0	20

*Magnetic Permeability.*—Tests were made on rings machined from normalised bar. The rings had a diameter of 14 millimetres, and after machining were heated to 950° C. *in vacuo* and slowly cooled over a period of thirty-six hours. They were brought into successive steady cyclic states of *H* and *B*, and from the corresponding values the following table and the curves in Fig. 28 were obtained. The grain-size of rings 31 and 24 is illustrated in Fig. 15 (Plate VI.), A and B respectively, at a magnification of about 2 diameters.

The density was measured and found to be 7.90.

Ring No. 2323, E24. High Oxygen.			Ring No. 2324, E31. Low Oxygen.	
H.	B.	$\mu$ .	B.	$\mu$ .
0.2	250	1,250	1,300	6,500
0.4	800	2,000	8,500	21,300
0.6	2,400	4,000	11,400	19,000
0.8	6,100	7,630	12,600	15,800
1.0	9,000	9,000	13,220	13,200
1.5	11,670	7,780	14,000	9,330
2.0	12,730	6,370	14,370	7,190
3.0	13,700	4,570	14,770	4,920
5.0	14,560	2,910	15,110	3,020

The hysteresis loss was measured at various values of  $B_{\max.}$ , and the law connecting hysteresis loss and  $B_{\max.}$  was found to be approximately of the form :

$$\text{Loss in ergs per cubic centimetre per cycle} = \eta B_{\max.}^{1.6}.$$

The value of  $\eta$  for each material was determined :

$$\text{E24, ring No. 2323}/\eta = 0.00076.$$

$$\text{E31, ring No. 2324}/\eta = 0.00029.$$

The permeability curves obtained for the two rings are shown in Fig. 28.

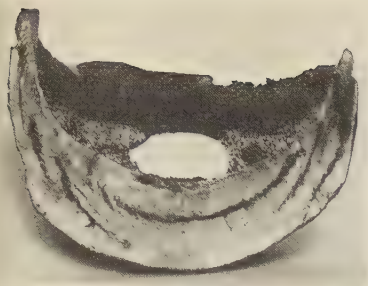


FIG. 9.—Full size.



FIG. 10.—Full size.



FIG. 11.— $\times 100$ .



FIG. 12.— $\times 100$ .



FIG. 13.— $\times 100$ .



FIG. 14.— $\times 100$ .

NOTE.—Figs. 11 to 14, 17 to 23, 25 to 27 have been reproduced  $\frac{2}{3}$  original size.  
Figs. 9, 10, 15, 16, 24 have been reproduced full original size.]

[To face p. 112.]





FIG. 15.— $\times 2$ .

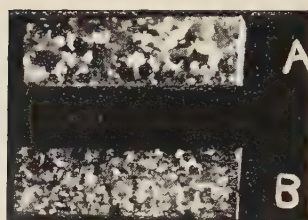


FIG. 16.—Full size.

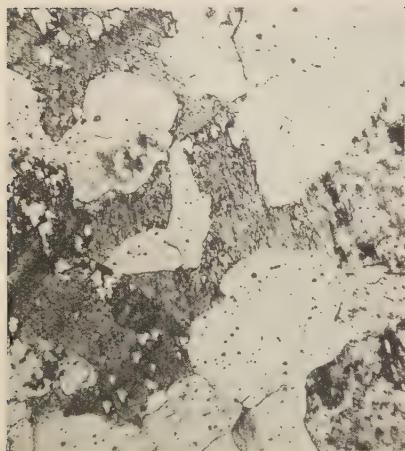


FIG. 17.— $\times 50$ .



FIG. 18.— $\times 100$ .



FIG. 19.— $\times 80$ .



FIG. 20.— $\times 150$ .



FIG. 21.— $\times 150$ .

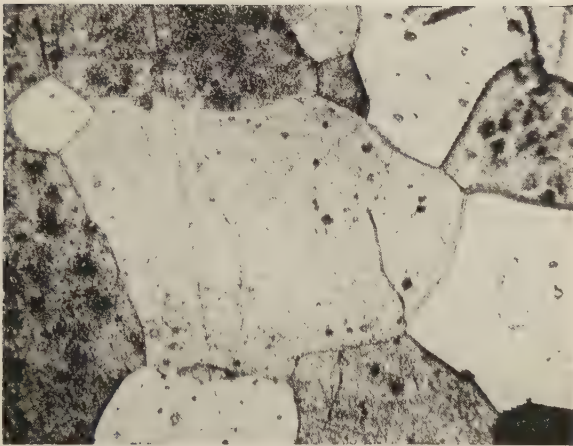


FIG. 22.— $\times 150$ .

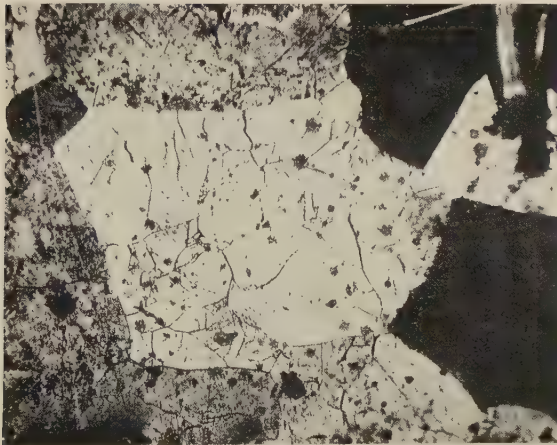


FIG. 23.— $\times 150$ .

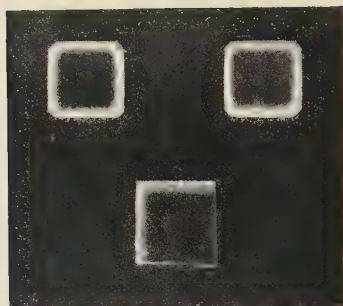


FIG. 24. Full size.

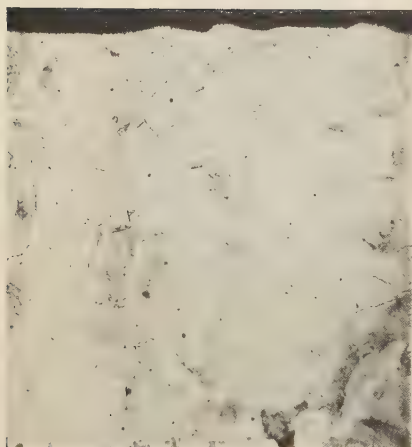


FIG. 25.— $\times 100$ .

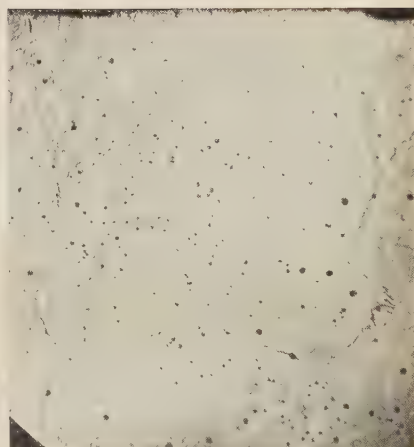


FIG. 26.— $\times 100$ .



FIG. 27. — $\times 500$ .

To compare the properties of this material with those of other materials of high maximum permeability corresponding curves were drawn to the same scale as for ring No. 2324 for a sample of Permalloy,<sup>1</sup> and for a sample of good annealed silicon iron. These are given in Fig. 29, and show  $B/H$  curves over a range  $H = 0$  to  $H = 1$ ; Fig. 30 shows the hysteresis loss curves over a range  $B_{\max.} = 0$  to  $B_{\max.} = 10,000$ .

In connection with the following tests, it is important to note

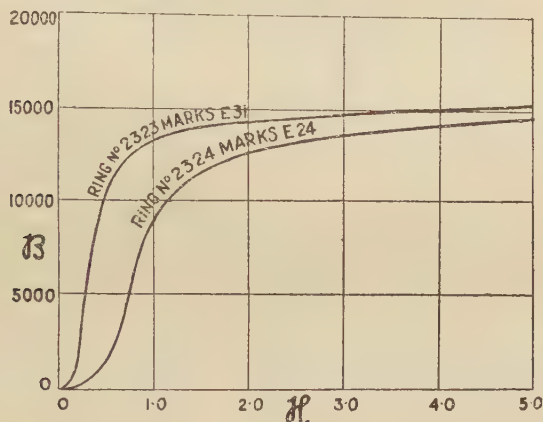


FIG. 28.

that the amount of material available from each ingot was only about 1 foot of rolled bar,  $\frac{1}{2}$  inch in diameter, and the amount of reduction of section during rolling of the ingots was about 80 percent. In most cases duplicate tests have not been possible, and the results are therefore to be considered as indicating only approximately the properties of the materials. Some differences may be found when larger ingots are used.

*Tensile Tests.*—Both the samples on p. 115 consist mainly of a saturated solid solution of oxygen in iron, and the sole difference between them is that the low oxygen sample contains in addition relatively few particles of free oxide, whereas the high oxygen sample contains a very large number of such particles. The conclusion appears justified that dissolved oxygen does not

<sup>1</sup> The data for Permalloy were obtained experimentally at N.P.L. from a sample supplied by the Western Electric Co. Slightly higher values for the permeability are reported by Arnold and Elmen, but the general type of the curve is not different from that herein recorded.



greatly alter the strength or ductility of iron, but that free oxide particles have an embrittling effect in the cold without

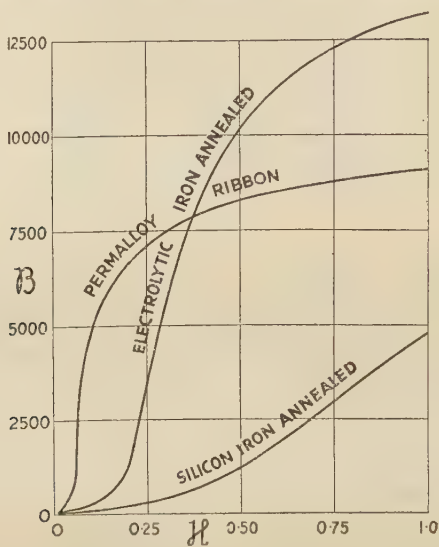


FIG. 29.

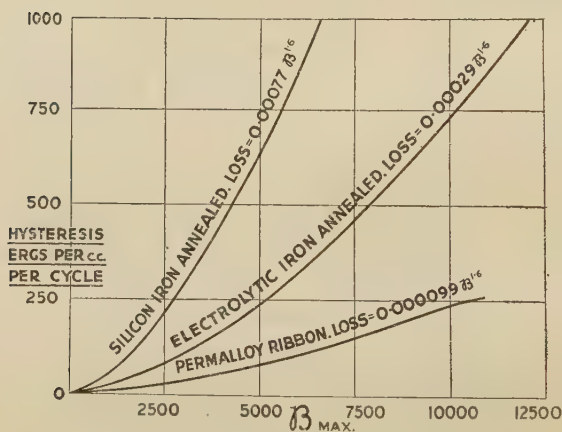


FIG. 30.

any marked strengthening effect. The limit of proportionality of these materials is very low, probably as a result of the absence of any appreciable amount of dissolved impurity in the iron.



Identification Marks on Bar.	E31, Low Oxygen. Normalised in Air.	E24, High Oxygen. Normalised in Air.		E11, High Oxygen. Normalised <i>in vacuo</i> .	
Diameter of test-piece (inch) . . . .	0.3573	0.2377	0.219	0.358	0.218
Limit of proportionality (tons per square inch) . . . .	2.5	4.3	...	3.7	...
Yield stress by drop of beam (tons per square inch) . . .	8.3	9.3	...	6.9	...
Ultimate stress (tons per square inch) . .	15.2	*	16.2	*	18.7
Modulus of elasticity (lbs. per square inch)	$29.9 \times 10^6$	$29.5 \times 10^6$	...	$29.5 \times 10^6$	...
Extension (gauge length = $4 \times \sqrt{\text{area}}$ ) per cent. . . .	50	*	7	*	10
Reduction of area at fracture (approx.), per cent. . . .	80	...	2	...	4

\* This test-piece fractured in the screw thread. The test-piece was turned to a smaller diameter and re-tested in order to obtain the ultimate stress, elongation, and reduction of area, which are given in the next column.

*Impact Tests.*—The results of notched-bar tests by the Izod method are as follows :

*Results of Tests.*

N.P.L. Eng. Dept. Test-Mark.	Identification Marks on Samples.	Energy absorbed in Foot-lbs.
BUQ1C	E31 (low oxygen)	3.2
BUQ2G	E24 (high oxygen)	1.1

The results show the material to be brittle under impact. One of the causes of this brittleness may be the coarse grain-size of the iron. The crystal sizes of the test-pieces E31 and E24 are illustrated in Fig. 16 (Plate VI.), A and B respectively, at natural size.

*Hardness Tests.*—Brinell hardness tests were made with a ball

of 5 millimetres diameter and a load of 750 kilogrammes applied for thirty seconds. The diameters of the impressions were measured in two directions at right angles, and the hardness numbers calculated from the formula :

$$H = \frac{W}{A}$$

Where  $H$  = hardness number ;

$W$  = load in kilogrammes = 750 ;

$A$  = spherical area of the impression in square millimetres calculated from the mean diameter.

*Results.*

Mark on Test-Piece.	Mean Diameter of Impression. Mm.	Hardness No.
E31, BUQ1C (low oxygen)	3.52	66
E24, BUQ2C (high oxygen)	3.46	69

Scleroscope hardness tests were made on the sides of the impact test-pieces with a universal hammer, and using the glucose method of supporting the specimens.<sup>1</sup> The following results were obtained : E31 = 18 ; E24 = 17.

*Fatigue Tests.*—Fatigue tests were made on  $\frac{3}{4}$  inch diameter bars, the ingots having been reduced 60 per cent. in cross-section during rolling. The bars were annealed *in vacuo* at 950° C. before machining.

The following material was tested : F8, high oxygen.

*Results.*

N.P.L. Engineering Test-Mark.	Identification Mark.	Range of Stress, Tons per Sq. In.	No. of Alternations.	Remarks.
BXXI.	F8, high oxygen	± 6.95	13,090,000	Unbroken
		± 7.80	10,500,000	"
		± 8.66	13,930,000	"
		± 9.50	10,500,000	"
		± 10.35	13,850,000	"
		± 11.20	3,470,000	Broken

<sup>1</sup> Tritton, "The Use of the Scleroscope on Light Specimens of Metals," *Journal of the Institute of Metals*, No. 2, 1921, vol. xxvi.

The low oxygen bar was not tested, owing to an accident to the test-piece.

The ratio of fatigue range to maximum stress is relatively high, namely, about 1.2: the fatigue range may have been raised slightly by "under-stressing" during the test, as only one specimen was available for the determination of the fatigue range.

### COLD-ROLLING.

As a small amount of material was still available for test further experiments were made in cold-rolling. Pieces 3 inches long of the  $\frac{1}{2}$  inch diameter bars of high and low oxygen content were heated to 950° C. and cross-rolled to form sheets 0.08 inch thick, in five passes. These pieces were then normalised in an electric furnace in air at 1000° C. and cold-rolled, using small pinches of  $\frac{2}{1000}$ ths of an inch at first and later reducing the pinch to  $\frac{1}{1000}$ th or less when the metal began to harden. The low oxygen sheet rolled to 0.04 inch without cracking, but the high oxygen sheet cracked badly at 0.078 inch. A piece 1 inch wide was now cut from the low oxygen sheet, and a small piece  $\frac{1}{2}$  inch wide, which did not appear to be cracked, was selected and cut from the high oxygen sheet and further cold-rolled as before. The low oxygen sheet rolled to 0.0035 inch without cracking, but the high oxygen sheet began to crack all over at 0.05 inch. Another very small uncracked portion was then cut from the sheet and was further rolled to 0.005 inch successfully.

The experiments appear to support the results of physical tests in showing that iron containing 0.1 per cent. oxygen has considerable ductility both hot and cold, but the effect of increasing the oxygen content to 0.23 per cent. makes the iron "cold-short" and seriously impairs its ductility.

### THE EFFECT OF CUPRIC REAGENTS ON IRON CONTAINING OXYGEN.

In view of the statement by Le Chatelier that the results of etching steel with a cupric reagent were probably due to the presence and distribution of oxygen rather than phosphorus, a number of specimens of iron having various oxygen contents

were etched with the Rosenhain and Haughton (or "N.P.L.") cupric reagent and Stead's cupric reagent.

No difference of the etching properties of ingots melted in hydrogen, vacuum, or air was found, the polished specimens etching up rapidly and showing a macro-etch of the crystal structure. Specimens of cold- and hot-rolled rods showed crystal distortion where this was present, but after normalising the specimens no indication of the direction of rolling was found, the etch only revealing a polyhedral crystal structure. If the specimens were etched for a sufficient time, a uniform layer of copper was deposited. The structures shown in Figs. 15 and 16 (Plate VI.) were obtained with the N.P.L. cupric reagent. It was observed that cold-work and distortion of the metal affected the etch considerably. The appearance of iron of high oxygen content etched with the aqueous cupric reagent is illustrated in Figs. 17 and 18 (Plate VI.) at 50 and 100 diameters respectively. In Fig. 18 some small white areas can be seen surrounding the particles of oxide. This is probably due, however, to slight local difference in the polish of the specimens where the hard oxide is situated.

An interesting method of etching was discovered during these experiments with cupric reagent. On certain specimens indications of a duplex structure were observed on some crystals, and it was later found that if the specimens were first etched for five seconds in 1 per cent. nitric acid in alcohol and afterwards for twenty seconds in N.P.L. reagent, this duplex structure was quite well developed in certain grains of the specimen. The etch revealed what appeared to be two sets of crystal boundaries. The appearance of the specimens etched in this manner is illustrated in Figs. 19 and 20 (Plate VI.) at a magnification of 80 and 150 diameters respectively.

These inner crystal boundaries have been previously observed by Andrews,<sup>1</sup> who obtained them by etching wrought iron in 1 per cent. nitric acid in water.

The first etching with nitric acid reveals the normal polyhedral structure of ferrite, as illustrated in Fig. 21 (Plate VII.), at a magnification of 150 diameters, the effect of further etching with the nitric reagent until the crystals are deeply attacked is shown in Fig. 22 and reveals very little more than is shown in Fig. 21. The effect of further etching the specimen with the cupric reagent

<sup>1</sup> *Proceedings of the Royal Society*, 1895, vol. lviii.

is shown in Fig. 23 at the same magnification, and shows what appear to be another set of crystal boundaries within a ferrite crystal. The same crystal of ferrite is illustrated in the three figures. These inner crystal markings are unaffected by heating the specimen to 850° C.

#### THE EFFECT OF CASE-HARDENING OXYGEN-IRON ALLOYS.

Small specimens of iron having high and low oxygen contents, together with a specimen of ordinary case-hardening steel for comparison, were case-hardened in the usual way by heating for four hours at 950° C., the box being cooled in air. The samples, which were approximately 1 centimetre cubes, were found to be well carburised. Etched sections of the specimens are illustrated in Fig. 24 (Plate VIII.) at full size, the sample carburised on two sides only being the steel. Microscopical examinations show that the depth of penetration by the carbon appeared to be quite unaffected by the presence of oxide, the depth of case being the same for all three specimens. No unusual features were observed in the pearlite which surrounded the oxide. The appearance of low and high oxygen iron after carburising is illustrated in Figs. 25 and 26 respectively at a magnification of 100 diameters, and Fig. 27 (Plate VIII.) at a magnification of 500 diameters illustrates how little the pearlite is affected by the presence of the oxide particles.

The specimens were afterwards quenched from about 850° C. in water. Subsequent micro-examination showed that all the specimens had hardened perfectly, and were completely martensitic in the "case," which is rather remarkable considering the purity of the steel.

The oxide particles appear to be practically unaffected by the carburising process or by the subsequent hardening operations. There appeared to be rather fewer of the very smallest particles of oxide in the case-hardened portion of the specimens than in the centres.

#### SUMMARY.

The main features of the work concerning the iron-oxygen system are as follows :

The freezing point of iron containing a little oxygen (about



0.08 per cent.) has been carefully checked in atmospheres of nitrogen and argon respectively. No difference was observed in the arrest points determined by these two methods, which gave a freezing point of  $1535^{\circ}\text{C}$ ., when referred to the melting point of palladium as being  $1555^{\circ}\text{C}$ .

The solid solubility of oxygen in pure iron is estimated to be about 0.05 per cent. of oxygen.

The liquid solubility of oxygen in iron at about  $1530^{\circ}\text{C}$ . is 0.21 per cent.; beyond this concentration of oxygen two liquid layers are formed.

The melting point of the oxide in contact with iron at high temperatures is found to be  $1370^{\circ}\text{C}$ .

No variation has been found in the lower arrest points of iron containing 0.12 per cent. to 0.21 per cent. of oxygen.

Iron containing 0.08 per cent. of oxygen can be rolled with ease both hot and cold, and the rolled material has good ductility in a tensile test. Under notched-bar impact tests, however, the material is very brittle.

The low results of these impact tests may be connected with the grain-size of the material, which was large. It was found difficult to produce a small grain-size in iron of low oxygen content by ordinary normalising methods. The absence of impurities no doubt facilitates the production of large grains.

The results of physical tests on rolled iron rods containing various amounts of oxygen show a marked decrease in the ductility of the iron, with increasing oxide content.

Iron containing low and high oxygen contents have been carburised and case-hardened without difficulty. The oxide particles appear to be practically unaffected by the case-hardening process.

No definite etching effects due to the presence of oxygen could be detected by means of cupric reagents.

The authors wish to acknowledge their indebtedness to Mr. F. Adcock, M.B.E., for his assistance in connection with the high-frequency induction furnace, and Mr. T. E. Rooney for estimating the oxygen content of the samples and other analytical work, and to Mr. R. P. Garner for his general assistance throughout the work.

## APPENDIX.

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## PART III.—THE ESTIMATION OF OXYGEN IN PURE IRON.

By T. E. ROONEY, A.I.C., A.M.S.T. (National Physical Laboratory).

THE estimation of oxygen in steel has been studied by a number of workers, and most of the methods employed are based on that of Ledebur. This method consists in reducing the oxide contained

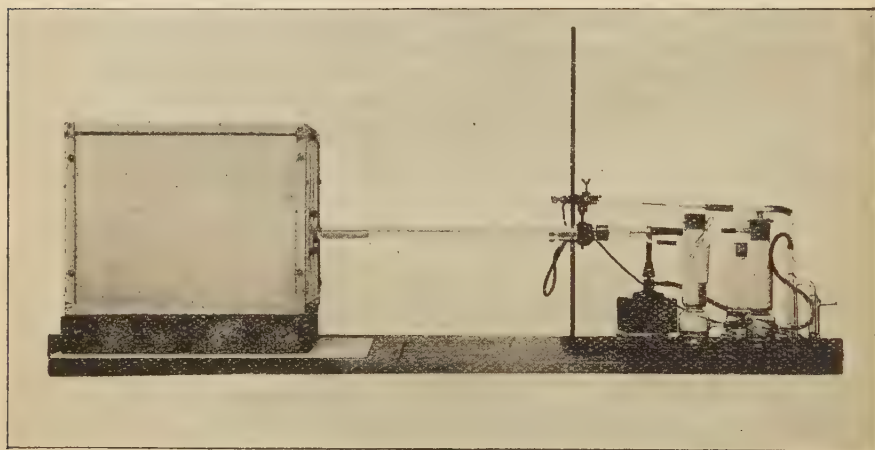


FIG. 31.

in the steel by heating the sample in a current of hydrogen and collecting and weighing the water produced.

In the present investigation the absence of appreciable amounts of the usual constituents of a steel, such as carbon, silicon, sulphur, manganese, &c., made the problem of estimating the oxygen less difficult, but the amount of any one sample available for analysis was strictly limited, and therefore the quantity that could be used in a single estimation was also restricted, and it became essential therefore to eliminate even minute sources of error (blank) as far as possible. This latter fact rendered Pickard's method<sup>1</sup> undesirable, as the blank is stated to amount to 1 or 2 milligrammes.

<sup>1</sup> *Carnegie Scholarship Memoirs*, 1913, vol. v.

As a result of preliminary work it was decided to use calcium chloride as a drying agent, as recommended by Blair,<sup>1</sup> and the apparatus shown in the photograph, Fig. 31, was designed in some respects similar to the apparatus used by Pickard.

#### DESCRIPTION OF APPARATUS.

The furnace consists of an alundum tube wound with platinum ribbon, the ribbon being secured at the ends with silver wire, which formed the terminals for the supply of current. The alundum tube is enclosed in a fireclay tube and is kept in position by collars made of Mabor brick.

The space between the tubes is packed with ignited alumina powder. The furnace tubes thus fitted are fixed in a box or casing made of Uralite sheet, and held in place by bolts attached to the Mabor ends or collars. The box is packed with magnesia packing.

It is possible to obtain a temperature of about 1300° C. in this furnace.

The reduction is carried out in a tube of transparent vitreous silica (1 inch diameter, 24 inches long) closed at one end. This tube is fitted with a glass cap shown in the diagram, Fig. 32, the joint between the cap and the tube being secured by a piece of stout rubber tubing which fits on the outside of the quartz tube, and a gas-tight joint is made when the glass cap is pushed on over all.

The glass cap carries (1) a silica delivery tube, which reaches to the closed end of the quartz tube, and (2) an outlet tube.

The delivery tube is connected to a tower containing granular calcium chloride, and the tower communicates with a bottle containing a small amount of sulphuric acid to act as an indicator of the gas current. The sulphuric acid is also useful to indicate when it is necessary to recharge the calcium chloride tower and the absorption tube. The sulphuric acid bottle is connected through a short length of silica tube to the fine adjustment valve of a hydrogen gas cylinder. This silica tube is heated to a red heat in order to remove traces of oxygen from the hydrogen.

The absorption or weighing tube is filled with small-grained calcium chloride, and is connected to the outlet tube in the glass cap on one side and to a calcium chloride tower on the other. A

<sup>1</sup> "Analysis of Iron and Steel." Eighth edition.

bottle containing sulphuric acid, cadmium acetate, or other absorbent is connected at the end to act as a gas current indicator, and also to allow the gases given off to be examined.

The silica reduction tube is held in a clamp on a retort stand with a large base, and the whole of the purifying and absorption

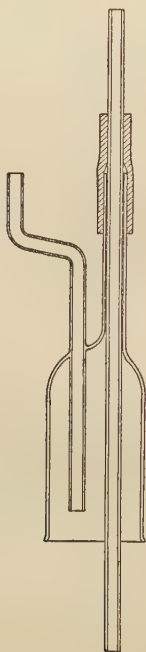


FIG. 32.

apparatus is carried on the same base, so that the silica tube can be moved into or out of the furnace.

The temperature of the furnace is regulated by means of a variable resistance, and a platinum-platinum rhodium thermocouple is used for indicating the temperature.

#### PREPARATION OF SAMPLE.

The samples were prepared in the form of very fine millings, precautions being taken during machining to avoid contamination by oil, grease, dust, &c. It was found advisable immediately a



sample had been milled to dry the millings in a stream of dry hydrogen.

By the exercise of great care during the milling operation and by this process of drying in hydrogen directly afterwards, it was not found necessary to heat the sample in nitrogen, as recommended by Law.<sup>1</sup>

#### METHOD OF CARRYING OUT THE ESTIMATION.

Two to 5 grammes of the millings were weighed out into a silica boat, and the boat was placed in the silica tube and pushed up to the closed end. The glass cap was then fitted on and hydrogen passed through the apparatus until the weight of the absorption tube was constant. The hydrogen in the weighing tube was replaced with dry air before each weighing. When the weight of the absorption tube had become constant, the quartz tube was moved into the furnace, so that the boat occupied the centre of the heated region. The heating was continued for one hour before the first weighing of the absorption apparatus. It was found in preliminary experiments that the best temperature for complete reduction lies between  $1150^{\circ}$  and  $1200^{\circ}$  C., and the time required is about two hours. This is in agreement with the results obtained by Oberhoffer and Keil,<sup>2</sup> and is also in accordance with the work of Whiteley.<sup>3</sup>

Experiments were carried out on lines similar to those of Whiteley, to determine the depth to which the reduction of the oxide was effected by heating in hydrogen at a temperature of  $1200^{\circ}$  C. A small specimen containing about 0.20 per cent. of oxygen, as indicated by microscopic examination, was heated for a period of three hours at  $1200^{\circ}$  C. in a stream of hydrogen.

After cooling the specimen was cut through the centre and the cut face was polished. An examination of this surface showed that reduction was not complete for more than about  $\frac{1}{2}$  millimetre from the surface.

The use of the finest possible millings for this estimation is therefore essential. Reduction could be accelerated by using a

<sup>1</sup> *Journal of the Iron and Steel Institute*, 1907, No. II.

<sup>2</sup> *Stahl und Eisen*, October 13, 1921.

<sup>3</sup> *Journal of the Iron and Steel Institute*, 1920, No. II. p. 143.

faster stream of hydrogen, but there is a danger in this case of the moisture produced not being completely retained in the absorption tube.

The employment of temperatures above  $1200^{\circ}\text{C}$ . resulted in the reduction of the silica in contact with the millings with the formation of silicide of iron and water vapour, and even at  $1200^{\circ}\text{C}$ . there was sometimes a slight reaction between the millings and the silica.

At a temperature of about  $1300^{\circ}\text{C}$ . for two hours the millings were found to have combined with 0.30 per cent. of silicon. This fact limited the employment of temperatures higher than  $1200^{\circ}\text{C}$ . Attempts were made with the boats of various compositions, such as alundum, magnesia, &c., to avoid this difficulty, but boats made of these materials gave a large blank even after repeated heating in hydrogen at  $1200^{\circ}\text{C}$ .

The millings were weighed after reduction and an estimation of the silicon content made in order to determine if any reaction had taken place between the iron and the silica. In this way a check was kept on the percentage of oxygen obtained by weighing the amount of moisture collected in the absorption tube.

In addition to the method just described a method described by Oberhoffer and Keil<sup>1</sup> was also employed. A similar apparatus was used for the purpose, but as the temperature did not exceed  $1000^{\circ}\text{C}$ . an ordinary furnace wound with nichrome wire was used instead of the platinum-wound furnace, and also the length of the silica tube was cut down.

The method consists in heating the millings with a proportion of an alloy of antimony and tin and collecting and weighing the water vapour produced in the ordinary way.

An alloy containing about 60 per cent. tin and 40 per cent. antimony was used by the present author. The temperature was maintained between  $950^{\circ}\text{C}$ . and  $1000^{\circ}\text{C}$ ., and about 15 grammes of alloy were added to 5 grammes of millings.

This method gave fairly consistent results, but they were in some cases appreciably lower than those obtained by the high-temperature method. (See Table II.)

<sup>1</sup> *Stahl und Eisen*, October 13, 1921.

## BLANK.

Blank tests were carried out on the apparatus from time to time. The boat was inserted in the silica tube and the tube was heated up to  $1200^{\circ}\text{C}$ . for a period of three to five hours.

The blank obtained in this way was very small, never exceeding 2 milligrammes on five hours heating and usually being less than 1 milligramme.

Care was taken to eliminate as far as possible any long connections with rubber tubing, and rubber joints were made with stout pressure tubing.

Weather conditions seemed to have the greatest influence on the blank, as on very damp days it was sometimes impossible to obtain concordant results.

## CONCLUSIONS.

As the result of estimations carried out at different temperatures and for varying times, it appeared that the best temperature for complete reduction is between  $1150^{\circ}$  and  $1200^{\circ}\text{C}$ .

At lower temperatures a fairly constant figure for the percentage of oxygen present could be obtained after two hours heating, and this figure could not be appreciably increased by prolonging the heating for a considerable time. Also increasing the speed of the hydrogen stream gave this constant figure in less time, but further heating did not give any appreciable increase. Examples are shown in Table I.

TABLE I.—*Effect of Temperature on Apparent Oxygen Content of the Same Sample.*

Temperature. Deg. C.	Percentage of Oxygen Found. Per Cent.	Remarks.
900	0.09	{ H. at rate of 100 c.c. per minute.
1000	0.14	
1000	0.15	
1100	0.16	
1150 to 1200	0.19	
1000	0.17	Alloy method.

Table II. shows the results obtained on a number of samples, using the alloy method and the reduction at 1150° to 1200° C.

TABLE II.

Sample.	Alloy Method. Per Cent.	Reduction at 1150° to 1200° C. Per Cent.
1	0·09	0·09
2	0·10	0·11
3	0·15	0·15
4	0·14	0·15
5	0·17	0·19
6	0·19	0·19
7	0·18	0·21
8	0·20	0·21
9	0·27	0·29

It is suggested that the problem of reducing the oxide in a mass of iron depends not on the facility with which the hydrogen gas penetrates into the metal, but on the ease with which the water vapour formed can escape.

In an attempt to deoxidise a sample of electrolytic iron, which was in the form of relatively large pieces, the sample was heated in hydrogen for some hours at a temperature of 1200° C. After cooling, the sample was stored for some days in an atmosphere free from moisture, and it was noticed that rust formed on the surface, which seems to indicate that water vapour had been trapped in the mass of the material and, on storing, caused rusting.

## DISCUSSION.

The PRESIDENT, in opening the discussion, alluded to the very wide interest that a scientific institution such as the Iron and Steel Institute would have in the subject of the paper. The financial question involved had been before the Institute and other leading scientific institutions of the country, and the fine example of Sir John Dewrance and his personal liberality had been a great spur to the various scientific institutions in coming to the help of the fund. He would not say more in that connection, because Sir John was a personal friend of his, and he would get into serious trouble if he said too much, but undoubtedly the example of a few gentlemen like Sir John Dewrance, who were able to stand by a research of the kind described in the paper, influenced not only the scientific institutions but the Government in realising the great importance of developing such scientific research. He further desired to emphasise that it was quite impossible for such a *magnum opus* as was represented in the paper to be undertaken in any other way than by such an institution as the National Physical Laboratory. No one in the research laboratory of a large works could possibly concentrate his attention sufficiently upon the matter, or provide the necessary staff and time for the carrying out of such a wide investigation as that referred to in the paper. The paper was one of those outstanding instances of the advantage of the existence of the National Physical Laboratory, staffed, as it was, by very eminent scientific men whose thoughts were free to be concentrated on a great work of the kind described. It could not be carried out by any other means, because it would be impossible to interfere with the everyday routine work that had to be done by men in works research laboratories. The authors were obviously only at the beginning of their task. They had undertaken a very large and important responsibility, and it was obvious that the work could only be completed if they received continued and generous help on the part of the public and the scientific institutions for the purpose of providing the necessary funds for carrying on the work.

Sir ROBERT HADFIELD, F.R.S. (Past-President), expressed his admiration for the excellent manner in which the authors had carried out their labours. As one of the Committee appointed to arrange the programme of the work to be undertaken, he hoped the results set forth in the paper would meet with the approval of the members. Certainly he was sure it would not have been possible to find anyone better qualified to undertake the supervision of such an important piece of research than Dr. Rosenhain, who had given so much time and

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attention to studying metallurgical questions of various kinds. The Committee therefore felt they were safe in his hands, and he thought that had been proved by the admirable manner in which the research had been started. They were also deeply indebted to Sir John Dewrance for the time and encouragement he had given to this research. He noticed that Professor Carpenter, who was a colleague of his on the Committee, was present at the meeting, and was sure that he (Professor Carpenter) would bear him out in the statement that the members could have but little idea of the amount of pains and trouble that Sir John Dewrance had taken in connection with the matter as well as by his handsome donations. Sir John had to appeal for help at a time when money was not easy to obtain, but he had stuck to his task from beginning to end, and he was sure Sir John must feel satisfied with the results that were now put before the Institute. In dealing with the question of alloys he desired to mention a point which would, perhaps, give those present some idea of the magnitude of the research that had been undertaken. For example, taking 23 binary alloys consisting of 23 separate elements added to iron, it would be found that the total possible number of ternary alloys, using those 23 elements, was 253; while the total number of quaternary alloys, using the same 23 elements, was 1771. That gave some idea of the enormous problem which had to be faced by the Research Committee. It also indicated the great length of time required for carrying out the work, and that too much must not be expected at the start. He thought Dr. Rosenhain had set a wise example by thoroughly investigating, in the first place, the qualities of the basic metal itself, iron. In the three sections of the paper that had been read there were set forth the leading points that had to be considered in connection with that metal. Personally, he would not call it a "base" metal in one sense of the term; it was a very noble metal. Metallurgists were indeed proud of the metal iron, and the wonderful combinations which could be effected with it. He hoped Dr. Rosenhain would not think he was trying to anticipate his work in any way, but as one who had studied the alloys of iron and manganese to a very large extent, he was naturally looking forward with great interest to the first results to be presented in regard to that particular combination of iron and manganese with no carbon. Just before the war commenced he (Sir Robert) carried out a large series of investigations in that direction. Unfortunately, owing to the serious pressure of war time and that existing in post-war conditions, he had not been able to put forward the results he obtained, but he hoped it might be possible in the future to place before the Institute an account of some portion of the work that had been done, because he thought it would be interesting to compare such results with those obtained by the Ferrous Alloys Research Committee. He hoped the members would appreciate what the investigation of an alloy meant. It was necessary, first of all, to consider its composition, which might nowadays include a large number of elements

—seven, eight, or nine—and in some cases more, because it was sometimes found that, after it was thought all the elements had been determined, one had been forgotten which might have great influence. For example, in the past no one thought very much of the effect that might be produced by copper with regard to its resistance to corrosion. It had now been found that the presence of a small percentage of copper might have a considerable influence on the alloy examined. It was necessary, likewise, to bear in mind the effects of the gases present, and if carbon were present, its form, and its particular carbide or combination of carbides. There were, moreover, the physical qualities or characteristics of the material, such as gases, melting point, soundness, toughness; the various physical qualities, such as elasticity, tenacity, elongation, reduction of area, shock qualities, Brinell hardness, electrical resistance, specific magnetism, and other properties. The question of the forging qualities also had to be considered. It was necessary to determine the question of the nature of the material as forged, as normalised, and as heat-treated. In heat treatment alone there might be numberless subdivisions. It was also necessary to examine the material for durability, corrodibility, and expansion qualities. Those, therefore, who had made a special study of such questions knew how wide were their ramifications. It will be seen, however, that the research had been started on an excellent basis, and he could not help thinking that before long most important results would be obtained, not only from the scientific point of view, but also from that of the practical application of the results obtained by scientific work—a point which the Institute and those guiding the work had always desired to have fully in mind.

Professor C. H. DESCH, F.R.S. (Member of Council), said that everyone who was working on iron alloys would recognise that the authors had begun a work on one of the most difficult of systems. The system iron-oxide-silicon—a knowledge of which was of such great importance to metallurgists in connection with steel manufacture—had been abandoned by the Geophysical Laboratory at Washington, on account of the impossibility of finding vessels which would resist the action of fused iron oxide. The authors had shown most remarkable skill in overcoming difficulties of that nature. The members could feel satisfied that the equilibrium diagram shown on p. 109 really did represent very nearly the condition of things that existed when iron and oxygen alone were present. He desired to make a few remarks with regard to the experimental methods adopted. The method of glazing the interior of the crucible by means of an arc seemed likely to be very generally useful, and he thought should be quite applicable in such cases. It did not seem to be very difficult to carry out, and most laboratories should be able to improve their crucibles in that way. The method was already used in the manufacture of silica ware, but its application to magnesia and substances of that kind should greatly

extend the usefulness of those materials. By starting work with an Ajax furnace the authors had sacrificed themselves for the benefit of other experimenters. Sheffield University now had an Ajax furnace, but after it had been ordered some of the difficulties which presented themselves at the National Physical Laboratory were dealt with, and the firm supplying the furnace made use of the experience gained at the National Physical Laboratory in designing the Sheffield furnace, which was of somewhat larger capacity. It was nominally 35 K.V.A. instead of 25 K.V.A., and a rather higher efficiency was being obtained from it. On the first occasion on which it was run no difficulty was experienced in melting 10 kilogrammes of a mixture of electrolytic iron and ferro-chromium, which ran down in about forty minutes completely fluid, so that the working of the furnace was very satisfactory. The furnace was built in England, and not in America. The Ajax furnace, with its extraordinary convenience, was likely to be a most useful implement of research in the future. The results obtained in the work carried out described in the paper were, on the whole, surprising, particularly in regard to the effect of oxygen in solid solution. The solubility of oxygen in the solid iron was estimated at 0.05 per cent. The quantity, of course, was small, but it was to be expected that it would exert a considerable influence. The tests, however, showed only a small difference in the properties obtained. Excess oxide injured the metal, but the oxide in solid solution seemed to have little effect. It was particularly surprising in connection with the experiment described on p. 119 on case-hardening, in which the presence of the oxygen seemed to have no effect in preventing the diffusion of carbon or the formation of normal pearlite. Everyone who worked with steel in general practice knew that from time to time steel would be found which contained particles of oxide, and which had around that oxide an entirely abnormal condition of pearlite. That showed itself very well in carburisation experiments, and it was to be found often in tool steels. Even in a 0.9 carbon steel specimens were occasionally found in which there were particles of oxide, and around that oxide were areas which etched quite differently from the ordinary steel. Such steels were specially difficult to harden. It was difficult to attribute that effect to anything but oxygen. At the same time, the results contained in the paper were so definite that he could not see any fault to be found with the conclusions, and it could only be presumed that in the ordinary steel it was not the effect of oxygen on the iron that was in question, but the effect of oxygen on one of the dissolved metals, possibly manganese. It was certainly a fact that in those steels they were not dealing simply with alloys of iron, oxygen, and carbon, but that there were always other substances present; so that the effect belonged to a ternary or quaternary system which was a real one. The bad effect of oxygen on carburisation and the hardening of tool steels was not an imaginary thing, but it did not appear to be connected with the influence of oxygen on iron. He was

also a little surprised at the small effect on the magnetic properties of a small quantity of oxygen in solid solution. Part III. of the paper, for which Mr. Rooney was responsible, would be very valuable to all those members who had to make such estimations as those described, which were extremely difficult. In regard to the estimations which had to be made in most works laboratories, he was afraid they were faced with the old difficulty that no method which depended on reduction by hydrogen would determine oxide alone if slag inclusions and other impurities were present. Investigators were still looking for an analytical method which would give them, without any ambiguity, the amount of iron oxide present in a metal as distinguished from silicates or other oxides.

Dr. W. H. HATFIELD (Sheffield) thought the paper contained an account of experimental data which, as the President had said, was a most fitting field of investigation for such an institution as the National Physical Laboratory and the various universities in the country. The fundamental work which had been carried out was of such a nature, and required such close attention, that it was extremely difficult in works research laboratories to do work of the same nature. Speaking on behalf of the steelworks research laboratories, he desired to say that the data given in the paper related to the particular kind of work that they looked to the National Physical Laboratory to place before them. The National Physical Laboratory had done a great deal of a similar type of work in connection with the non-ferrous industries, but the present paper related, he thought, to the first constructive basic work that had been done by them on steel metallurgy. He could not emphasise too strongly that the paper dealt with perhaps the most important problem which steel-makers had to consider—namely, the relationship of oxygen to iron. He could not help thinking, after carefully reading the paper, that, excellent though the work was, and convincing though most of its conclusions were, yet a portion of the diagram up to 0.21 per cent. of oxygen might very usefully receive far more intensive and extended investigation on the part of the authors, who, he believed, would share his views in that respect. For instance, there was no intrinsic evidence in the paper if oxygen was, and if so to what extent, in solid solution in iron. With regard to the quantitative results given in the paper, he was sure that the authors' figures for the percentage of oxygen which could be associated with iron in the solid state as distinct from a solid solution were correct. The members of the Institute might remember the very valuable paper which was presented a few years ago by Mr. Wesley Austin, in which he melted pure iron in the presence of an excess of oxide of iron, and arrived at precisely the same figure for saturation as the authors had obtained. The reason for his (Dr. Hatfield's) very intense interest in the paper was that he desired to obtain further information. Extending the work from the experimental conditions dealt with by the author, not



only himself but the whole steel world wanted to know what was the equilibrium content of oxygen in, say, an open hearth under an oxidising slag. The work the authors had done in the present instance naturally led towards that information, but at the moment it did not give it to them. He further wished to state that many of the members would, he was sure, be delighted to send to the authors, and to Mr. Rooney in particular, very interesting samples of ferrous products upon which they could employ the excellent method of determining oxygen which Mr. Rooney had devised, so that some really reliable data might be obtained as to the oxygen content. Undoubtedly the determination of oxygen was extremely difficult. On Plate VII. the authors referred to a double boundary test. As a matter of fact, he personally dealt with that matter before the Faraday Society some two years ago, and the explanation was very simple. The explanation was that the adjoining crystal was lowered by solution, and the double boundary was merely a view of the other surface of the adjoining crystal. If a transverse section were cut through the micrographic section the step down would be seen, and actually demonstrate the remarks he was making. He was sure the members would look forward with very great interest to a continuation of the fundamental researches dealt with in the paper. He agreed with Sir Robert Hadfield's statement that the authors had much work before them to do. He thought Sir Robert was extremely moderate in the estimate he had given of the number of alloys which he predicted required investigation. He hoped the authors would live long enough to complete the work, and that the members would live long enough to discuss it on future occasions.

Professor H. C. H. CARPENTER, F.R.S. (Member of Council), desired to say that, in his opinion, the data contained in the paper represented some of the best work which had ever been done in metallography, at any rate some of the most difficult. Anybody who had worked at the temperatures dealt with by the authors realised that there was a tremendous difference between working at 1200° C. and 1300° C., and working at 1500° C. and 1600° C. He thought that few if any previous investigators had attempted to do what the authors had not merely attempted, but had succeeded in doing—namely, in determining the equilibrium of a metallic system in such a high range of temperature. That would have the effect of setting the standard for a new type of work for which the National Physical Laboratory was eminently fitted, which certainly any university teacher could carry out with the greatest difficulty. At last he thought it could be said that something was known about the equilibrium of iron and oxygen. Some of the points to which he had intended to refer had already been mentioned by Dr. Desch, and he therefore did not propose to cover the same ground again. He desired, however, to deal with one other point which also emphasised the very small influence of oxygen on the metal,



namely, on its freezing point. Twenty years ago Mr. Keeling and he (Dr. Carpenter) published the first experimental determination of the freezing point of iron, in which they gave the value  $1505^{\circ}$  C. on the thermo-junction scale. Four years later, in reviewing that value (several determinations had been made in between) he came to the conclusion that the value of  $1519^{\circ}$  C. on the optical scale was more probable. In their experiments no precautions were taken to exclude oxygen. It would be seen that the difference between  $1519^{\circ}$  and  $1535^{\circ}$ , which was the highest value given in the paper, was only  $16^{\circ}$  C. There was a certain amount of uncertainty even with regard to that figure, and therefore he thought note should be taken of the fact that, at any rate as far as the freezing point of iron was concerned, oxygen could be said to be almost without influence. He would like to know whether the authors endorsed that opinion, but it seemed to follow from their paper, and if so, he thought that conclusion was not unimportant. Like Dr. Desch, he was quite willing to accept the diagram. Its simplicity appealed to him greatly, and he could assure the authors that it would appeal still more to the students on whom he was obliged to inflict equilibrium diagrams.

Professor H. LOUIS (Member of Council) said he desired to ask a question on a point which was not quite clear to him. Dr. Rosenhain and his colleagues had spoken of the iron-oxygen system, and of the solubility of oxygen in iron. He desired to know if that was strictly correct. Were they not really dealing with an iron-iron-oxide system, and should not they speak of the solubility of oxide of iron in iron rather than of oxygen? That criticism might seem to be trivial, but when results were obtained of such importance as those placed before the members in the paper just read, he thought the least the authors ought to do for their excellent work was to express it in unexceptionable language. For a scientific man, next to the importance of doing strictly accurate work came the importance of expressing it with strict accuracy. Incidentally, he would like to protest against Dr. Rosenhain following the prevailing fashion by speaking of an "alloy" of iron and oxygen. Personally, he would as soon think of calling salt an alloy of sodium and chlorine. He had been taught that an alloy was a combination of one or more metals,<sup>1</sup> and if so, obviously "an alloy of iron and oxygen" was not a correct expression. In scientific work strict accuracy of expression was of the utmost importance, and that might be, perhaps, a justification for calling attention to the matter.

Colonel N. T. BELAIEW, C.B. (London), said he desired to associate himself with the remarks made by previous speakers in regard to the excellence of the work done by the authors, who were now at the beginning of a whole series of work which would occupy a large amount of time. The valuable information contained in the present paper

<sup>1</sup> See e.g. "The New English Dictionary."

led the members to expect a great deal in regard to what would follow in the future.

All the other points he intended to raise had been more or less dealt with by the previous speakers. It had been noted by several speakers that the actual influence of oxygen on iron in solid solution in the solid state was, under certain circumstances, not so large as they had previously been led to expect. It seemed to him that in order to ascertain the exact influence of any alloy element or of any impurity, one of the most important factors was the structure of that impurity. For instance, dealing with iron oxides in iron in the solid state, if the structure of those oxides was a spherodised one, a much larger amount of oxygen than would otherwise be the case could be allowed to pass into the iron without any detrimental influence.

Mr. F. W. HARBORD, C.B.E. (Vice-President), said he desired to associate himself with the previous speakers in the remarks they had made expressive of their great admiration of the way in which the research had been carried out. He did not know any better example of the enormous amount of work which was involved in carrying out scientific research. Each difficulty as it arose had been faced and systematically investigated and dealt with. It was an example which should commend itself to all the younger metallurgists who were commencing scientific research work. He was not quite sure that melting iron and an oxide together would necessarily have the same effect as if the metal was oxidised by generating the oxide within the mass, as in the case of the Bessemer converter. Very little was known about such things at present. When the oxide was generated under the conditions such as obtained in steelworks practice, he thought it was conceivable that there might be, owing partly to the intimate association of the two substances, a greater degree of solubility *in situ* in the other, and also that the effect of the generation of the oxide *in situ* might to some extent have a slightly different effect on the physical properties of the steel than when the two substances were simply melted together. It would be very interesting if the oxygen in overblown samples from a basic Bessemer converter were determined with the object of seeing whether the amount present was appreciably greater than in the samples the authors had been examining. He knew there were great difficulties in what might be called Bessemerising small quantities of steel, but in view of the great ability shown by the authors in devising methods for overcoming other difficulties, he had no doubt that when they were able to experiment with larger quantities of steel such difficulties would be easily overcome.

Mr. J. E. FLETCHER (Dudley) said that on behalf of the Research Associations that were studying in a more practical manner the questions which Dr. Rosenhain and his colleagues had dealt with, he desired to express the deep debt of gratitude they owed to the authors for their

work. The equilibrium diagram was of great interest to all students of ferrous metallurgy, and the points that had already been raised in connection with it were of very great importance, especially when dealing with processes involving the use of pneumatic methods for the production of iron and steel such as those referred to by Mr. Harbord. For instance, the foundry cupola as well as the converter had to be considered, and the Cast Iron Research Association was particularly interested in the influence of oxygen and of oxidation on the product, cast iron. He desired to refer also to wrought iron. Some of the members knew that a rather long series of experiments had been carried out with a view to producing iron mechanically, and the point that Mr. Tritton had referred to in regard to the lining of vessels subjected to liquid iron oxide attack had there arisen. Very considerable difficulty was experienced in the rotary furnace in obtaining the glazed condition referred to. Eventually they were successful in getting that glazed condition, and the method was successful. That had some bearing in the larger and more practical sense on the points that had been brought forward in that connection. From a practical point of view, he was looking forward to obtaining a great deal of help from the work carried out by the authors. He thought a question might be raised in regard to the small samples of material that had been experimented with, for the purpose of giving the results of physical tests, and that possibly some question might arise as to whether the statements made concerning the mechanical properties of such iron could be definitely assumed to be correct. Larger samples might give considerably different results. He thought the permeability curves given in Fig. 28 on p. 113 were incorrectly marked; he was under the impression that they should be reversed.<sup>1</sup> Armco iron was of interest to all those who were studying the problem of wrought iron manufacture, and it would be intensely interesting if parallel results could be given both of the cooling and heating curves of Armco iron (with special reference to the oxide arrest at 1370° C.), in comparison with the iron that had been made by Dr. Rosenhain and his colleagues. It would also be interesting to have an analysis of the materials that were compared in Figs. 28 and 29. He thought it would also be useful if, in connection with the research proceedings, a full bibliography could be given of the work that had already been done on the subject.

Mr. J. H. WHITELEY (Saltburn) desired, in the first place, to congratulate the authors on the excellent work they had done. He thought great praise was due to them for the skilful way in which they had tackled the difficulties. He wished especially to point out how interesting the paper was in connection with certain reactions that took place in the steel furnace. For example, on p. 101 it was shown that, at 1300° C., ferric oxide was not entirely reduced to ferrous oxide by pure iron. He had obtained a similar result by heating mixtures of

<sup>1</sup> [This has since been done.—EDITOR.]

electrolytic iron and its oxide ( $\text{Fe}_2\text{O}_3$ ) in plugged cylinders of Armco iron at temperatures between  $1300^\circ$  and  $1400^\circ \text{C}$ .<sup>1</sup> The reduction of the  $\text{Fe}_2\text{O}_3$  by the iron in this way was never complete; usually about 8.0 per cent. remained. It seemed, therefore, clear that the reaction was a reversible one; that was to say, if pure  $\text{FeO}$  could be heated in a neutral atmosphere some iron would be formed by decomposition, according to the equation—



No doubt the equilibrium constant would vary with the temperature. The reaction seemed well worth further study, since it should be possible, at any rate under certain conditions, by means of it to arrive at an approximate idea of the free iron oxide content of open-hearth slags from their ferric oxide content. Again, Mr. Rooney referred, in his section of the paper, to the reduction of silicon by iron in the presence of hydrogen. He (Mr. Whiteley) could corroborate that statement, for by melting pure electrolytic iron in a silicon tube in an atmosphere of hydrogen he had obtained as much as 0.5 per cent. of silicon in the metal. It was well known that in the acid process the silicon content of the bath could be considerably increased at times by reduction of the silicon in the slag, and he suggested that that reduction might be facilitated by the hydrogen known to be present in the molten metal. The duplex structure to which the authors referred was one he had obtained repeatedly by a similar etching method, and he had always regarded it as indicative of the presence of oxygen, since it was always present in over-oxidised samples he had prepared. Moreover, it was often to be seen in puddled iron, which, of course, was made on an oxide hearth. He was therefore very pleased to have the author's confirmation of his deduction with regard to this particular structure.

The PRESIDENT said that, before calling upon Dr. Rosenhain to reply to the very interesting discussion that had taken place, he desired to offer to Dr. Rosenhain and his colleagues, first of all, the warm thanks of the members, and, secondly, their deep sympathy with them in the great work they had undertaken. It was evident from what had been said in the course of the discussion that the authors would have to devote a very considerable amount of effort and study to the question under consideration, and he hoped the fact that their work was of such great interest to the members of the Institute would encourage them in their prosecution of it. He could not imagine a work more easily and more suitably handled than by an eminent metallurgist of Dr. Rosenhain's standing, coupled with the assistance of his colleagues at the National Physical Laboratory and the use of all the equipment which existed there. If the result of their labours did not spell success, it should at any rate spell useful work. He hoped the vote of thanks

<sup>1</sup> *Journal of the Iron and Steel Institute*, 1921, No. I. p. 285.



he now had the pleasure of moving to the authors would be an encouragement to them, from the point of view that they knew that their efforts were appreciated by the members, and that they would thus be spurred on to further efforts to solve the difficult problem they had undertaken.

The resolution of thanks was then put and carried with acclamation.

Dr. WALTER ROSENHAIN, in reply, said it was a great privilege to him to reply to what was ordinarily a formality, but which on the present occasion was very much more. The President was quite right in thinking that in undertaking a task of the kind dealt with in the paper the authors needed encouragement and help of every kind. As the President had pointed out, the National Physical Laboratory had received a large amount of very substantial financial help from the Institute and many other institutions, and the authors hoped they might rely upon its continuance if the work was to be proceeded with. That, however, was an aspect of the matter which he was not anxious to emphasise, but he could not help saying, on behalf of his colleagues and himself, including those colleagues who were not immediately concerned with the paper in question but with the research in general, that they appreciated most deeply the sympathy and interest which had been shown in their work at the present meeting. It was of the greatest value to have personal encouragement in connection with a task which was not only extremely large, but sometimes almost dishearteningly difficult. The authors knew perfectly well that at the best they could not hope themselves personally to see the task through to the end, but they felt that they were part of an organisation which would outlive them, and that that organisation and the Institute would some day see the end of the work.

There was only one point in the discussion to which he wished to refer, namely, Professor Louis's question with regard to the nomenclature which had been adopted. First of all, he desired to ask Professor Louis whether he had any reason for believing that the form in which iron contained oxygen in the solid solution was oxygen or iron oxide? The probability was that in the solid solution the elements held in solution were present in the atomic condition, and it was probably more correct to speak of a solid solution of oxygen in iron than oxide. It was impossible to be dogmatic about it. With regard to the system iron-oxygen, it was true that the authors had confined themselves to the region up to one particular oxide only, but that was not the end of the system. The system in the last resort was the system iron-oxygen, and since oxygen in the form of a particular oxide might undoubtedly play a large part, he thought they were justified in speaking of the iron-oxygen system. With regard to calling such things alloys, he thought that anyone who was accustomed to dealing with steel, which was an alloy of iron and carbon, could hardly confine



the term to alloys of metal with metal. He did not think Professor Louis would call carbon a metal; they had all heard of alloys of copper and phosphorus, copper and arsenic, and so forth. He thought the definition suggested by Professor Louis was too narrow. In the present instance it was quite true that a body existed which formed well-marked chemical compounds with iron, but so after all did carbon, and so did phosphorus. He thought the authors were quite as justified in calling those metallic bodies alloys as many other systems of the kind.

Dr. D. HANSON, in reply, said his colleagues and himself would find the discussion very encouraging in pursuing their work further, and the appreciation which the paper had met with would be very helpful.

It had been stated by Dr. Hatfield that part of the diagram up to 21 per cent. of oxygen ought to receive more intensive investigation. The authors agreed with that statement, and recognised the shortcomings of the diagram in that region. Their difficulty so far had been that they had not been able to melt pure electrolytic iron under conditions which would give a melt entirely free from oxygen. Even when the melt had been reduced previously at  $1200^{\circ}\text{C}$ . in hydrogen and then remelted *in vacuo* in an induction furnace, about 0.08 per cent. of oxygen was still found in the resulting melt. That was an experimental difficulty that had not yet been overcome, so the authors could not claim to have obtained iron entirely free from oxygen, as all the iron was saturated with oxygen; the results obtained showed that oxygen in solid solution had no deleterious effect on iron. The material the authors obtained was extremely ductile, soft, and very free from brittleness in the tensile test or the rolling test, although it showed a considerable degree of brittleness under impact. He agreed with Dr. Hatfield's suggestion that the extension of the work to the open-hearth furnace was one of the things that ought to be done, but up to the present the authors had not been able to take up that portion of the work. It really meant extending the binary system and making an investigation of the ternary or more complex systems, because the slag was not simply iron oxide, and it could not be assumed that the behaviour of iron in contact with the ordinary open-hearth furnace slags would be the same as in contact with comparatively pure iron oxide. He was afraid Dr. Hatfield had misunderstood Mr. Tritton's statements with reference to the double boundaries. Mr. Tritton was not referring to a boundary that appeared to be a double line under the microscope but a double set of boundaries—that was, one set of boundaries within another. Dr. Hatfield's explanation of the double boundary was quite correct, but it was not what was meant by Mr. Tritton. Professor Carpenter had pointed out that the melting point of iron had been determined frequently in the past, and that the results obtained did not differ very greatly

from those that had been obtained by the authors, having regard to the difficulties of measuring temperature in that region. That was quite true. The highest value that the authors suggested was  $1535^{\circ}\text{C}$ ., and that referred to the new value for the melting point of palladium. If they referred to the old value for the melting point of palladium the melting point would be  $1530^{\circ}\text{C}$ ., which was not very different from  $1519^{\circ}\text{C}$ ., having regard to the difficulties of investigation in that range. In reply to Colonel Belaiew, it seemed probable that the effect of oxide would be much greater if it were distributed in a different form. In the low oxide melts studied a considerable number of rounded oxide particles existed, but they had little effect on such properties as the ductility in the tensile test or the cold-rolling properties. If those particles had distributed themselves round the grains, as did, for example, iron sulphide, a very different result might have been expected. When the number of those particles was increased largely they did exert some embrittling action, in much the same way that oxide particles in copper rendered copper cold-short when the oxygen content was high. The two cases were very analogous. Mr. Harbord asked if the authors could say whether more oxide would be present if the oxide were generated in the metal. He thought probably more oxide would be introduced in that way, and the authors had a little experimental evidence which confirmed that statement. In making their larger melts they melted about 480 grammes of iron in an induction furnace. That melted metal swirled round very rapidly in the pot, and the oxide content of those melts was rather greater than in the cases in which the two were melted quietly together. The authors thought that was due to the mechanical entanglement of a little more of the oxide globules in the molten metal than would be the case if the melting were done quietly. If oxide were generated in a vessel like a converter, the metal was being agitated and the oxide particles in the steel were being stirred up, so that an appreciably greater amount might be obtained than under simple melting conditions.

### CORRESPONDENCE.

Mr. FRANK GILL (International Western Electric Company, London) wrote that the sample of Permalloy from which Messrs. Tritton and Hanson obtained their curves for Permalloy was supplied by the International Western Electric Company Incorporated. The results obtained by the authors gave on the whole lower values of permeability than those given by Messrs. Arnold and Elmen in their article "Permalloy," published in the *Electrician* of June 22, 1924. The values obtained by Messrs. Tritton and Hanson were evidently not representative, but that might be due either to imperfect heat treatment or to mechanical

strains in the subsequent handling.<sup>1</sup> In paragraph 76 on p. 783 of the *Physical Review* for June 1924, some particulars were given by O. E. Buckley which threw some light on the way in which the magnetisation of the material could be modified and controlled by mechanical stress.

Mr. J. G. PEARCE (Birmingham) wrote that the Cast Iron Research Association had viewed the research on ferrous alloys with considerable interest. In its later stages that work should throw considerable light upon the fundamental properties of cast iron which were now being studied by his Association. A series of castings representative of the whole range of British grey irons, as well as special irons used for resisting heat, corrosion, abrasive wear, &c., had been produced under very carefully controlled melting conditions, and the test results—physical, chemical, and microscopic—were being collated. That work would shed considerable light on many hitherto puzzling phenomena regarding the relation of properties and constitution of cast iron, and would enable first approximations to be made towards conclusions the work done by Dr. Rosenhain should ultimately completely reveal. The method pursued at the National Physical Laboratory through the use of the purest possible materials, studied by the most refined methods of measurement available, could not fail to give more accurate results in the long run, although it would be slower and more costly.

The fear had been expressed that the work of two independent bodies in one field of research, both charged with the expenditure of funds partly derived from Government sources, would result in overlapping, but those who were acquainted with the work being done did not share that view. The work done at the National Physical Laboratory was essentially complementary to that being pursued by the Cast Iron Research Association, and the latter body would welcome an opportunity of becoming associated with the Ferrous Alloys Research and contributing its quota of experience in discussing the work being done. The publication of further results on iron-manganese and iron-chromium would be awaited with keen interest, and it would be interesting to know the precise proposals with regard to iron-carbon, iron-silicon, and the non-metals.

Dr. HANSON and Mr. F. S. TRITTON, in further reply, wrote that they thanked Mr. Fletcher for pointing out the error in Fig. 28 on p. 113; the description of the two curves should, of course, have been reversed, and that had been corrected in the final proof of the paper.

The authors appreciated that the results of the physical tests must be considered to some extent provisional, since they were made on small samples of the material, but they saw no reason to suppose that specimens from larger melts would differ very greatly from those now described. The results obtained with their samples differed very

<sup>1</sup> [An explanatory paragraph has since been added in the paper by the authors.—EDITOR.]

greatly from the results previously obtained with other samples of commercial iron; they did not think that those differences were due simply to the small sizes of their melts, but that they represented real differences between the materials.

The authors noted Mr. Fletcher's suggestion that cooling and heating curves of Armco iron should be taken with reference to the oxide arrest at  $1370^{\circ}\text{C.}$ , and thought that that would be worth doing. They had not, however, done much work on Armco iron, because they had found from microscopical evidence that the oxide particles in Armco iron had a duplex structure, and the material differed so markedly in that respect from pure iron-oxygen alloys that they thought it would be somewhat difficult to interpret the results of cooling curves through the oxide arrest point without an extensive investigation.

The authors regretted that they could not supply detailed analyses of the materials that were compared in Figs. 28 and 29. Those materials were, however, typical examples of commercial products (the stalloy containing 4 per cent. of silicon).

The authors had prepared a short bibliography of the subject, as suggested by Mr. Fletcher, and that was now added at the end of the paper.

The authors thanked Mr. Frank Gill for his communication, and had added a paragraph in the text of the paper, pointing out that their values for the permeability of Permalloy were somewhat lower than those found by Messrs. Arnold and Elmen. The difference between the two sets of results was not great and did not alter the general character of the curves. They also wished to thank Mr. Pearce for his communication.

Mr. ROONEY, in reply to the discussion on Part III. of the paper, wrote that he was interested in the remarks of Professor Desch and Dr. Hatfield, but would like to emphasise the fact that the President had pointed out in opening the discussion, that the authors were obviously only at the beginning of their task. That remark applied equally well to Part III. of the paper, as the work that had been done was concerned only with the estimation of oxygen in pure iron.

The problem of estimating oxide of iron in slags and commercial steels might be rendered much less difficult by a systematic study, in the first place, of simpler combinations.

The author was glad to have the confirmation by Mr. Whiteley of the reduction of silica by iron in presence of hydrogen. That reaction was important from the possibilities it suggested, as, for example, the reduction of other oxides in presence of hydrogen and iron or in presence of iron and other reducing gases.

All those points were worth further study in connection with the estimation of oxygen in ferrous alloys and ferrous materials.





## Iron and Steel Institute.

### THE HARDENING OF STEEL.

BY WALTER ROSENHAIN, D.Sc., F.R.S., F.Inst.P.  
(THE NATIONAL PHYSICAL LABORATORY).

FEW metallurgical problems have been more fully and widely discussed and investigated than the hardening of steel, and at times the discussion has suffered from undue warmth of feeling. It would be difficult to justify a further paper on such a subject, whether advancing a new theory or criticising old ones, were it not that new light has been thrown on the phenomena of hardening metal by recent investigations on materials other than iron and steel. Since there is still an unduly sharp distinction between ferrous and non-ferrous metallurgy, it may be desirable at the present stage to bring before this Institute a review of the whole position. In undertaking such a review, it is not possible to avoid a definite theory of hardening; it will, however, be the author's endeavour to distinguish as far as possible between experimentally ascertained fact and deductions and opinions which cannot claim the same degree of certainty.

Until quite recently the phenomena of hardening and tempering of steel could rightly be described as unique, since no other alloy or metal was known in which analogous phenomena could be produced. It is not surprising, therefore, that the explanation of such a unique series of properties should be sought among other peculiarities more or less exclusively found in the case of iron. Such peculiarities are the allotropic transformations of iron and the power of that metal to hold carbon in solid solution at high temperatures. Theories of the hardening of steel based upon both these peculiarities were early developed, and the controversy between allotropists and carbonists is now a matter of history.

The recent discovery of closely analogous properties mainly in the alloys of aluminium, zinc, and to a lesser degree copper, has, however, opened a wider horizon, and, as will be shown below, it now appears that although both the allotropic transformations

of iron and the power to hold carbon in solid solution at high temperatures play a part in the phenomena of hardening and tempering, that part is in a sense an indirect one, and that for the explanation of the hardness of hardened steel, neither an excessively hard allotropic variety of iron nor an adamantine iron-carbon compound are necessary.

Perhaps the best way of approaching the present position of the subject is to describe, as briefly as possible, some of the outstanding phenomena connected with the hardening and tempering of certain non-ferrous alloys, in order to show the analogy which exists between these phenomena and the well-known behaviour of iron-carbon alloys. The explanation of the mechanism of hardening and tempering in the non-ferrous alloys, which has been fully established, will then appear as a general explanation of phenomena of this class, and its applicability to the particular case of steel can be considered.

The fundamental discovery of hardening phenomena in non-ferrous alloys was that made by Wilm in the year 1909, when he showed that certain aluminium alloys containing a small percentage of magnesium were capable of hardening. This fact, as it subsequently transpired, had already been discovered in the laboratories of the Royal Arsenal at Woolwich, but, in accordance with the general policy pursued at that time in connection with War Department researches, had not been published.

The hardening which occurs in aluminium or its alloys containing magnesium differs markedly, at first sight, from that to which we are accustomed in the case of steel. Steel, when heated to a temperature above the critical point and quenched, is fully hardened as soon as it is cold. The aluminium-magnesium alloys, of which the well-known "Duralumin" may be regarded as typical, are not appreciably hardened immediately after quenching. On the other hand, the hardness of the aluminium alloy increases with time after quenching, if kept at the ordinary temperature. The hardening is rapid at first, but the rate falls off and the maximum value is reached generally after a period of about four days. This behaviour is illustrated by the time-hardening curve, Fig. 1.

The discovery of Wilm, which led to the patenting of a number of alloys and their heat treatment, was made without any understanding of the real nature of the phenomena involved. The

discoverer himself frankly admitted that he was unable to offer any explanation for the changes which occur during the hardening of Duralumin, particularly as there is no obvious change in the microstructure between the material when freshly quenched and after it has undergone the four days' ageing. The changes which occur in Duralumin and similar alloys have, however, formed the subject of extensive investigations which have been

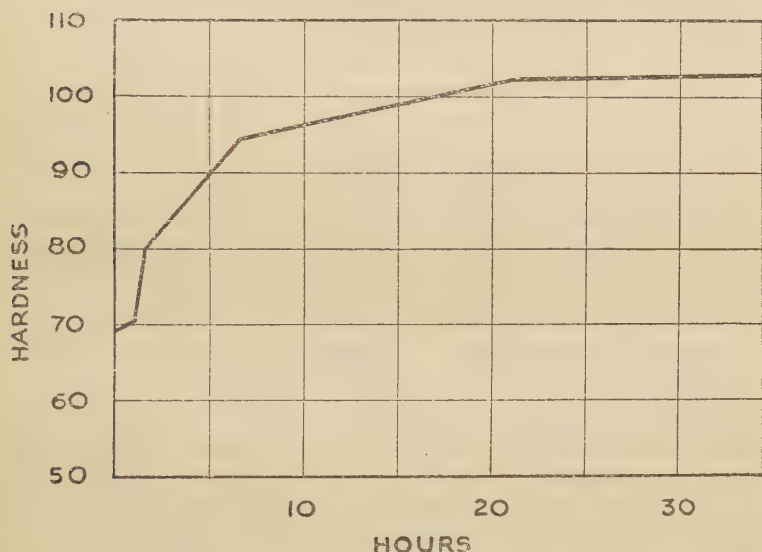


FIG. 1.—Time-Hardening Curve. Duralumin.

carried out mainly in this country at the National Physical Laboratory, and in America at the Bureau of Standards.

Both groups of investigators have arrived at a satisfactory explanation of the phenomena, although their explanations differed in detail. Subsequently, these differences have been completely reconciled, and the transformations which occur in alloys of this kind during quenching and subsequent hardening are now thoroughly understood.

It should perhaps be pointed out that this is the direct result of a systematic study in great detail of several groups of ternary and one portion of a group of quaternary alloys. This part of the work has been carried out mainly by Hanson and Gayler in

this country, and their conclusions have further been supplemented by an investigation of other alloys, including notably those of zinc and aluminium and of copper and iron.

An early stage in the investigation consisted in the study of the equilibrium diagram of the alloys of aluminium and magnesium.<sup>(1)</sup>

Although the equilibrium diagram arrived at in this research differs considerably from earlier diagrams published by German and other workers,<sup>(2)</sup> it did not exhibit any features which could account for the hardening of aluminium-magnesium alloys. The explanation was found in the discovery that silicon plays a part in the hardening of the alloys of aluminium and magnesium. Silicon is always present in commercial aluminium, and, indeed, the preparation of aluminium entirely free from silicon has not yet been achieved. It was, however, found that in the aluminium-magnesium alloys, when the amount of silicon was progressively reduced, the hardening effect was correspondingly diminished. It was also found that an alloy of the Duralumin type, as free as possible from silicon, showed very much less age-hardening than the normal material. In the search for the explanation of these phenomena, a study of the ternary equilibria of the system aluminium-silicon-magnesium was undertaken, but owing to the immense amount of labour involved, only the region of special interest in the present connection, covering the alloys rich in aluminium, has been studied in detail. The results have been published in the Eleventh Report to the Alloys Research Committee,<sup>(3)</sup> and more fully in a paper by Hanson and Gayler in the *Journal of the Institute of Metals*.<sup>(4)</sup>

It is unnecessary to reproduce here the equilibrium model and the various diagrams and sections which have been obtained by these authors. The point of principal interest is the existence of a well-defined compound of silicon and magnesium corresponding to the formula  $Mg_2Si$ , which is found to be capable of passing into solid solution in aluminium to a much greater extent at high temperatures than at the ordinary temperature. In thus thinking of the compound as passing into solid solution, it is not suggested that the compound as such is present in the solid solution, since it appears more probable, on general grounds, that silicon and magnesium atoms are scattered through the lattice of the alumi-

niun crystals. None the less, when the amount of silicon and magnesium present reaches the limit of solid solubility, the excess appears in the form of minute crystals of magnesium silicide,  $\text{Mg}_2\text{Si}$ . Fig. 2\* is a horizontal section of a portion of the ternary equilibrium model on which the limiting solid solubilities of silicon and magnesium, or of magnesium silicide in aluminium at a temperature of  $500^\circ\text{C}$ ., are indicated by the line  $x-y$ , the composition of the corresponding alloys being represented in the

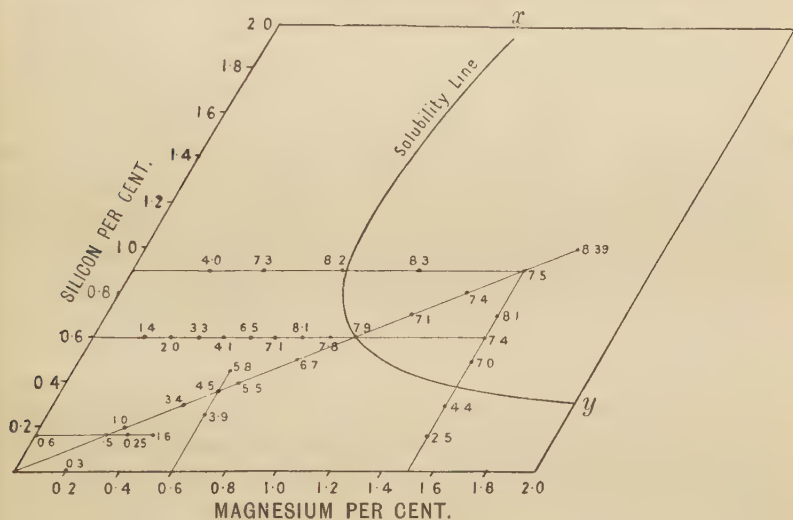


FIG. 2.—Horizontal Section of Part of Ternary Equilibrium Model, showing Differences in Tensile Strengths of Aged and Slowly Cooled Specimens.

usual manner on a portion of the equilateral triangle forming the basis of the ternary model. For a number of alloys of varying compositions the increase of hardness, due to age-hardening after quenching, is indicated on the diagram by numbers which show the increase in tensile strength by hardening in each case. A very striking result is seen. The hardening power of the alloys increases steadily as their composition approaches the line of limiting solubility,  $x-y$ . The maximum increase of hardness is obtained in alloys lying close to this line, but increase of either silicon or

\* This figure and Figs. 4, 5, 6, 7, 8, and 9 are reproduced by kind permission of the Institute of Metals.



magnesium, or both, beyond the amount which can be held in solid solution at  $500^{\circ}\text{C.}$ , results in no further increase in hardening power. The inference from this result is clear, that hardening is associated with the amount of silicon + magnesium which is present in solid solution at the high temperature when the alloy is quenched. This quantitative connection between hardening power and the amount of magnesium and silicon held in solid solution can be clearly traced in a variety of other ways, which have been described in detail in the papers already mentioned. They justify the inference that the age-hardening of aluminium-magnesium-silicon alloys of suitable composition is due to the separation from a supersaturated solid solution, obtained by quenching from a high temperature, of magnesium silicide in a state of very fine division. Microscopic examination shows that these alloys when quenched and examined immediately afterwards are homogeneous—that is to say, consist of crystals of a single solid solution only. After age-hardening there is no appreciable difference in microstructure, so that we are forced to the conclusion that the particles of magnesium silicide that have been deposited during ageing at the ordinary temperature are too minute to be traced by means of the microscope. On the other hand, if such an alloy be slowly cooled from a suitable temperature, so as to allow the excess of magnesium silicide to separate at a higher temperature, well-defined crystals of magnesium silicide are formed.

While the behaviour of aluminium alloys containing magnesium and silicon was being investigated at the National Physical Laboratory, a number of workers at the United States Bureau of Standards at Washington, including Merica, Waltenberg, and Scott,<sup>(5)</sup> investigated the alloys of aluminium and copper from this point of view. Here also a solid solution is formed in the case of alloys containing less than 4 per cent. of copper, which can be rendered apparently homogeneous by quenching from a suitable high temperature after an adequate period of annealing to bring the copper into solid solution. If slowly cooled from that temperature, crystals of the well-defined and well-known compound  $\text{CuAl}_2$  appear. If the alloy be quenched, the formation of these crystals is suppressed and the alloy appears to be a homogeneous solid solution. This also, on ageing, undergoes a certain amount

of hardening, and the American investigators attributed this hardening to separation of very minute particles of  $\text{CuAl}_2$  from the supersaturated solid solution. More recently Dr. M. L. V. Gayler, at the National Physical Laboratory, has examined certain groups of alloys containing aluminium, together with magnesium, silicon, and copper,<sup>(6)</sup> and has found that in these alloys age-hardening at room temperature is due essentially to the separation in a finely divided state of magnesium silicide,  $\text{Mg}_2\text{Si}$ , from the supersaturated solid solution formed during quenching. On the other hand, a further degree of age-hardening can be obtained by exposing the quenched alloys to temperatures in the neighbourhood of  $150^\circ$  to  $200^\circ \text{C}$ . for varying periods of time, and this further age-hardening appears to be due to the precipitation of the copper compound  $\text{CuAl}_2$ . The results of the two independent series of investigations are thus reconciled, and the explanation of the hardening of alloys of the Duralumin type, and of similar aluminium alloys in which supersaturated solid solutions can be formed by quenching, is placed on a satisfactory basis.

Taken by itself, the view of the nature of age-hardening in aluminium-magnesium-silicon alloys resulting from these investigations is still to a certain extent hypothetical, although the close quantitative relations which have been established afford a sound basis for the explanation in question. The generalised view of the phenomena of hardening, and of age-hardening in particular, derived from these researches is capable of verification in connection with other alloy systems. These verifications have been sought and obtained in several instances, so that the correctness of the general ideas upon which the explanation is based can now be regarded as established.

In the course of an investigation of the effect of impurities on copper being carried out for the British Non-Ferrous Metals Research Association, Hanson and Ford at the National Physical Laboratory have studied the alloys of copper with iron, so far as those consisting mainly of copper are concerned.<sup>(7)</sup> In the course of this investigation the solubility of iron in solid copper was determined, and it was found that at  $1100^\circ \text{C}$ . copper could hold 4 per cent. of iron in solid solution, while at  $750^\circ \text{C}$ . the solubility is reduced to less than 0.2 per cent. Consequently, if an alloy containing 0.7 per cent. of iron is held at a temperature of  $1000^\circ \text{C}$ .

and then quenched, a supersaturated solution of iron and copper is produced. In this supersaturated solid solution at the ordinary temperature no further change occurs, nor would any such change be anticipated in view of the fact that at the ordinary temperature this alloy is some  $1000^{\circ}\text{C}$ . below the freezing point. When, however, the temperature is raised to about  $500^{\circ}\text{C}$ . in order to allow of greater mobility, a change of the nature of age-hardening occurs. Measured in terms of Brinell hardness, there is a very appreciable change, the value increasing from 36 to 53, thus verifying the anticipation derived from the generalised view of the cause of hardening. In this particular case, however, there is not a corresponding increase in tensile strength, a fact which is possibly connected with the well-known peculiarity of copper in regard to correspondence between tensile strength and Brinell hardness. None the less, these alloys behave in the manner indicated by the general theory, although, quantitatively, the results are disappointing.

A much more striking verification of the general theory, and one which presents remarkable analogy in detail with the iron-carbon system, has been discovered by Hanson and Gayler in the alloys of aluminium and zinc. These authors <sup>(8)</sup> have established for these alloys an equilibrium diagram which is reproduced in Fig. 3. The metallographic data upon which this diagram is based are so complete and have been so carefully determined that there can be no reasonable doubt of its validity, which has been further confirmed by a Japanese worker using entirely different methods. <sup>(9)</sup>

The portion of this diagram which is of particular interest in the present connection centres around a triangular area marked with the letter  $\beta$ . In this region of temperature and concentration the alloys, when equilibrium has been attained, consist of a single homogeneous solid solution. If they are kept at this temperature for a sufficient length of time and then quenched, and immediately examined microscopically, they are found to consist of an aggregate of simple polyhedral crystals. This microstructure is illustrated in Fig. 4 (Plate IX.), which has been obtained by very rapidly polishing the quenched specimen so that it could be etched  $1\frac{1}{2}$  minutes after quenching. If, on the other hand, such an alloy be cooled slowly, and particularly if its com-

position correspond with the lowest point of the triangular area in question, it exhibits a structure which is indistinguishable from the pearlite of carbon steel. This is shown in Fig. 5; as the diagram shows, we are here dealing with a typical eutectoid in every way analogous to pearlite itself, and the striking correspondence of the microstructure is a remarkable confirmation of this view. We have here, however, a case in which a

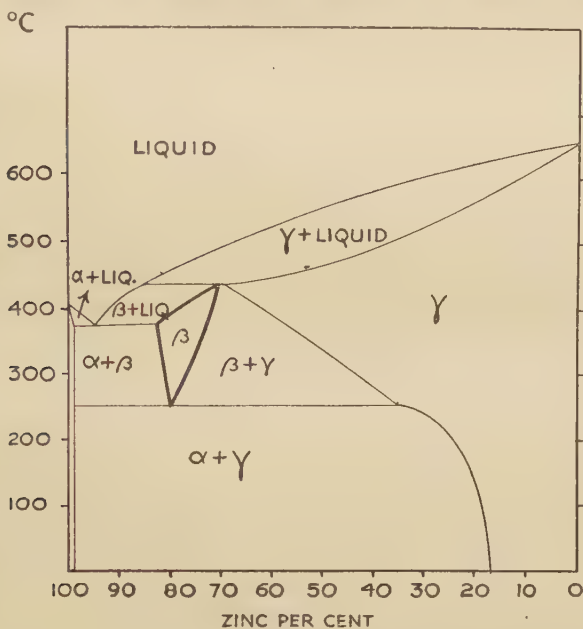


FIG. 3.—Al-Zn Diagram.

supersaturated solid solution can be obtained by quenching from a suitable temperature, and if this supersaturated solid solution can subsequently be decomposed in a suitable manner hardening should be anticipated. Actually, it is found that at the ordinary temperature the quenched supersaturated solid solution rapidly decomposes. If this process be studied under the microscope, a series of structures is found recalling in many respects the troostite and sorbite of carbon steel. Accompanying this is found first a rapid hardening followed by a gradual softening. These phenomena are well illustrated in

Figs. 6 and 7 (Plate IX.), which represent the microstructures of transition stages, and in Figs. 8 and 9, which give time-hardness and time-temperature curves on specimens of these alloys taken immediately after quenching. From Fig. 8 it will be seen that the hardness rises very rapidly at first and then gradually falls. This series of changes is accompanied by a marked evolution of heat. On the basis of the general theory which has been outlined above, these phenomena can be readily explained. The

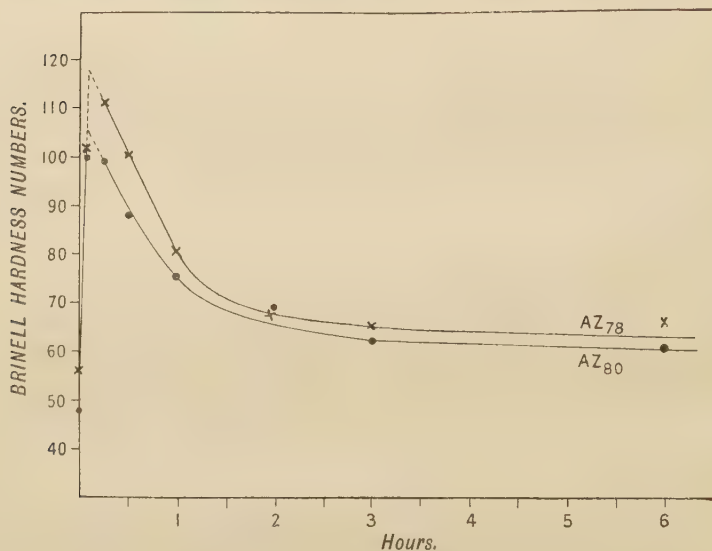


FIG. 8.—Al-Zn. Time-Hardness Curves.

supersaturated solid solution in this case at the ordinary temperature is too near its transformation temperature to remain in a metastable state, even for a short time. Consequently, the precipitation of the supersaturated solid solution, or rather in this case the breaking up of the metastable quenched  $\beta$  phase into the  $\alpha$  and  $\gamma$  phases of the aluminium-zinc system, immediately commences. The first stage of this separation results in the formation, probably simultaneously, of very minute crystallites of  $\alpha$  and  $\gamma$  in a state of extremely fine division. Such a structure brings with it a considerable increase in hardness. Were it possible to chill the alloys, as, for instance, in liquid air, at the precise



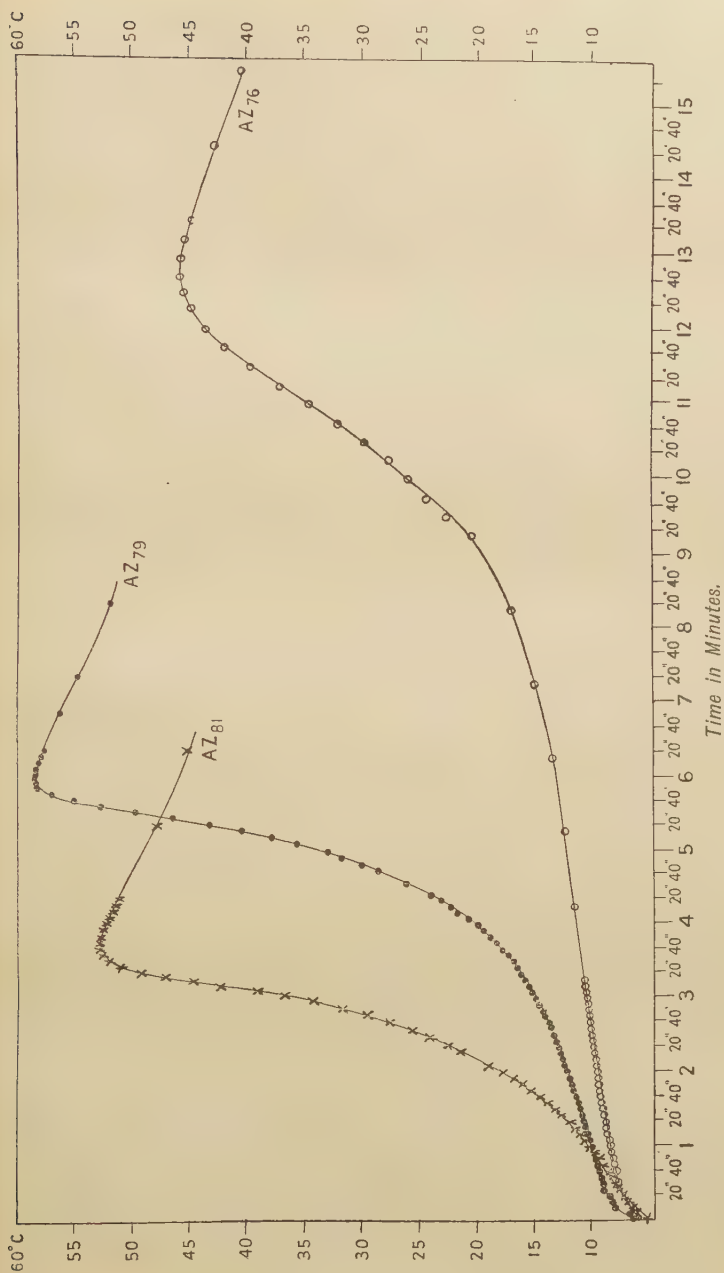


Fig. 9.—Al-Zn. Time Temperature Curves.

moment when they have reached their maximum hardness, there is every reason to believe that they would retain this hardness so long as they were maintained at a sufficiently low temperature. Actually, the experiment has been tried of chilling the alloys immediately after quenching, and in that case no hardening occurs. The subsequent changes which the alloys undergo can be readily explained in view of the successive microstructures which are observed. The very finely divided  $\alpha$  and  $\gamma$  phases coalesce into particles of increasing size with consequent diminution in hardness and a simultaneous evolution of heat. Ultimately, when the process has gone far enough, the hardness of the alloy is reduced very nearly to that of the original quenched solid solution. It will be evident at once that changes which occur after maximum hardness has been reached in these alloys are exactly analogous to the tempering of hardened carbon steel. Indeed, the whole of the phenomena, particularly in this system, are so closely analogous to those which are observed in steel that it is difficult to doubt that the same explanation is applicable to both.

The observations and inferences which have just been described with regard to non-ferrous alloys lead to the general view that hardening is the result of the breakdown of a supersaturated or unstable solid solution, such a supersaturated solution being obtained as a rule as the result of quenching. The question arises whether this general explanation of hardening is applicable to the special case of iron-carbon and alloy steels. There seems to be little difficulty in interpreting the phenomena which occur in steel in the light of these views. Actually, the analogy is so close that it appears to need little elaboration, but there are one or two outstanding points of difficulty which require consideration. In the first place, the hardening of a quenched carbon steel occurs during quenching and not subsequently by any such process as age-hardening. Actually, it has been shown that there are changes which occur in quenched carbon steels even at the ordinary temperature, and Hadfield and Brush<sup>(10)</sup> have shown that there is a gradual evolution of heat in a fully hardened carbon steel, thus completing the analogy with the quenched aluminium-zinc alloys just described. The fact, however, that a quenched carbon steel is fully hard as soon as it is cold points to a factor which

requires full consideration when comparisons are made between different metals and alloys in regard to such a matter. The exact behaviour of any particular alloy when quenched and subsequently held at a constant temperature must depend upon two factors. The first of these is the rapidity with which transformations or reactions occur in the metal, while the second is the relative position on the temperature scale of the temperature at which the alloy is held after quenching. In the case of the aluminium-zinc alloys, room temperature is only some  $240^{\circ}\text{C}$ . below the transformation temperature and only some  $450^{\circ}\text{C}$ . below the temperature of complete fusion. In the case of the aluminium-silicon-magnesium alloys, the transformation temperature is considerably higher than in the aluminium-zinc alloys, while the fusing temperature is also somewhat higher. In the case of a copper-iron alloy the ordinary temperature is very far below the melting point, and this is still more so in regard to iron and steel. We should therefore anticipate, as is actually the case, that while in the aluminium-zinc alloys transformations at the ordinary temperature are very rapid, they are markedly less rapid in the aluminium-silicon-magnesium system, still less rapid in the copper-iron, and slowest of all in the iron-carbon system. Put in another way, one may regard various alloy systems as having "equivalent temperatures" at which the behaviour is analogous. It is therefore not surprising to find that in the aluminium-zinc alloys, for instance, tempering after hardening takes place at the ordinary temperature, while in iron-carbon steel temperatures from  $350^{\circ}$  to  $500^{\circ}$  or  $600^{\circ}\text{C}$ . are required to bring about corresponding changes.

The fact that quenched carbon steels are fully hardened as soon as they are cold is a direct consequence of the well-known fact that it is impossible in straight carbon steels to retain the alloy in the form of a homogeneous solid solution (austenite) by quenching, however vigorous. Expressed in terms of the views here described, this simply means that the decomposition of the supersaturated or metastable solid solution occurs during the actual cooling process in the quenching operation itself. The validity of this view is confirmed by the fact that in the presence of suitable quantities of manganese or nickel, steels can be obtained in a fully austenitic condition by quenching,

and that when thus retained in a state of homogeneous solid solution they are not hard. Further, such austenitic steels, if they are of precisely suitable composition, can be subsequently hardened or converted into the martensitic condition by raising their temperature, while further rise of temperature or prolonged exposure to heat results in tempering and again softening them.

If the explanation which has been found so clearly and readily applicable to the non-ferrous alloys also applies to the alloys of iron, the hardening of steel must be ascribed to the breakdown of the  $\gamma$ -iron solid solution (austenite) either by the deposition of a dissolved phase in a finely divided condition, or by the simultaneous formation of two phases also in a very finely divided state. Fully hardened steel would therefore consist of extremely minute but crystalline particles of  $\alpha$ -iron and cementite in an excessively fine state of division. Such a state implies the existence in the material of a very large amount of intercrystalline boundaries. Whatever the nature of this boundary may be, there can be no doubt that an extremely fine aggregate of this kind must present enormous resistance to plastic deformation by any such process as slip. We have here the explanation, possibly, of the very much greater hardness which is obtainable in hardened steel as compared with the non-ferrous alloys of which we have spoken above. In the alloys of the Duralumin type, for example, we have in the usual hardened condition fairly large crystals of aluminium solid solution through which is dispersed a quantity of the compound  $Mg_2Si$  in an exceedingly fine state of division. The presence of an enormous number of these minute particles of a foreign body in the aluminium crystals must severely disturb their internal structure and interfere to a considerable extent with their ability to undergo plastic deformation by slip. It does not, however, by any means entirely destroy the mechanism of slip in these crystals, so that the resulting materials, although very much harder than in the annealed condition, are still appreciably ductile. By special treatment (prolonged heating at  $200^\circ C.$ ) the hardening can be carried further, until ductility almost disappears, but even then the degree of hardening is still much smaller than in steel. In an alloy of this kind complete hardening is not obtainable, because the maximum amounts of magnesium and silicon which can be held in solid solution do not yield a sufficient quantity

of precipitated material after hardening entirely to disrupt and destroy the crystal structure of the aluminium matrix. In the case of the iron-carbon alloys a different state of affairs prevails. Here the whole of the  $\gamma$ -iron solid solution undergoes transformation, and the simultaneous formation of minute crystallites of ferrite and cementite, possibly still more or less entangled with vestiges of the original  $\gamma$ -iron structure, results in a constitution in which a slip mechanism on any reasonable scale cannot exist. If such a structure is tempered—that is, if the particles are allowed to increase in size while they decrease in number—there will be a gradual reconstitution of a slip mechanism, at any rate in the ferrite crystals of the mixture, with the result that after a time an appreciable amount of slip mechanism can re-establish itself, so that we have with decreasing hardness an increasing degree of toughness and even of ductility.

On the basis of the views just explained, fully hardened steel (martensite) consists of a mixture of excessively finely divided ferrite and cementite. Such a structure is in accordance with the fact that steel in this condition is magnetic, and that under X-ray analysis it shows the atomic structure of ferrite. Without going into full details, it may be suggested that the majority of the properties of hardened steel can be readily accounted for by such a structure and constitution. There is, however, one outstanding feature in the microstructure of hardened steel which is not immediately accounted for by the explanation here put forward. This is the well-known acicular structure of martensite. In none of the non-ferrous alloys which have been studied in this connection has any closely analogous structure been observed. On the other hand, structures very similar to the needles of martensite can be found in other metals, which, while they do not appear to be capable of hardening, yet undergo allotropic transformations. Certain features which have been observed in the microstructure of cadmium by Jenkins, working at the National Physical Laboratory, show a striking resemblance to martensite and are undeniably associated with the allotropic transformations of cadmium. At the same time, it may be pointed out that martensite having a well-marked acicular structure is not necessarily hard. In steels of quite low carbon content, which undergo no appreciable degree of hardening as the result of quenching, a well-marked martensitic



structure is often developed, so that the connection between a martensitic structure and extreme hardness is perhaps rather accidental than causative. If the indications from the analogy of other metals can be trusted, one would be led to regard the acicular structure of martensite as associated primarily with the allotropic transformation of iron and only indirectly connected with the hardening process itself.

The explanation of the hardening of steel which has been put forward in the present paper has already been summarised in the words: "Hardening is due to the decomposition of a supersaturated or metastable solid solution obtained by quenching, such decomposition resulting in the production of a very large number of minute crystallites of one or more phases, either constituting the whole of the hardened material or scattered through a crystalline matrix." That a structure of this kind should possess, in some cases, an extreme degree of hardness is readily understood, since the softness and plasticity of metals in their ordinary condition are known to be due to the possibility of plastic deformation by a mechanism of internal slip in the crystals. Any disturbance of the regular crystalline arrangement results in a corresponding increase of resistance to slip, and therefore increase of hardness. If the disturbance of the structure be carried to the point where the slip mechanism is entirely destroyed or its functioning is eliminated, complete hardening results, and the degree of hardening in a given case will depend, in the first place, upon the exact extent to which the slip mechanism is disturbed, and in the second place, upon the actual cohesive strength of the metal in question. In hardened steel, both factors operate to produce maximum hardness. Iron itself, although very soft and ductile when in the pure state, possesses a high degree of cohesion; further, the simultaneous formation of  $\alpha$ -iron and cementite during the decomposition of  $\gamma$ -iron, as a result of the allotropic transformation of the iron itself, brings about a structural arrangement most completely preventing the occurrence of plastic deformation by slip.

The relation of this view to earlier theories of the hardening of steel may be of some interest. It will be seen that the part played both by allotropic transformation and by carbon is fully recognised, since the allotropic transformation gives rise to the

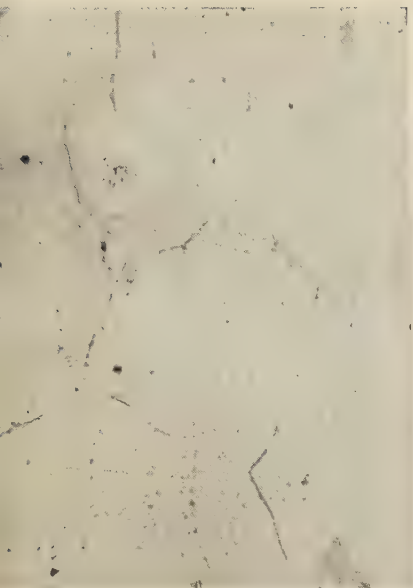


FIG. 4.—Al-Zn. 1½ minutes after quenching.

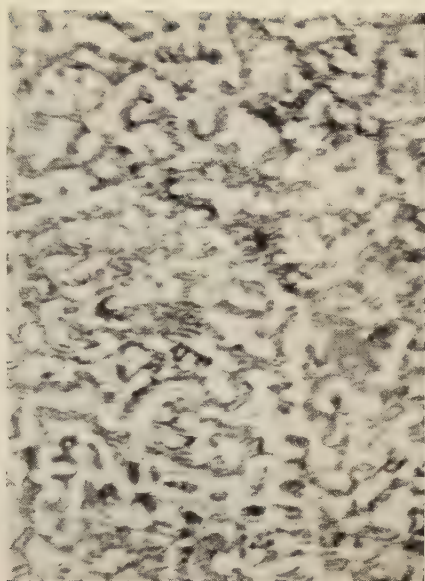


FIG. 5.—Al-Zn. Eutectoid.



FIG. 6.—Al-Zn. 2 minutes after quenching.



FIG. 7.—Al-Zn. 5 minutes after quenching.



sudden change in solid solubility, while the presence of carbon is necessary to furnish one of the two decomposition products of the solid solution. In one aspect also the present view is closely connected with the so-called amorphous theory of hardened steel suggested by the present writer in 1914. The kind of disturbance of the crystal structure of a solid solution which is produced by the formation in it of minute crystallites of a deposited phase may be described as rendering the substance more or less completely amorphous in the immediate vicinity of each of these crystallites. One of the main features of the amorphous state is the very absence of slip mechanism, which in the present view is regarded as being essential to hardness. It may, however, be claimed that the views put forward rest upon a wider and more solid foundation than many of the older theories. A large amount of new experimental fact has been obtained, and a whole range of phenomena has been discovered, which bring the behaviour of steel on hardening closely into line with phenomena observed in other alloys. It may perhaps be too soon yet to say that the mystery of the hardening of steel has been completely solved, but a large amount of new light has undoubtedly been thrown upon it.

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1924—ii.



## CORRESPONDENCE.

Colonel BELAIEW (London) wrote to express his appreciation of and very great interest in, the paper. The author was to be congratulated on having brought forward a general theory of hardening which would allow of the problem of the quenching of steel being considered in the light of modern researches on non-ferrous alloys.

In 1915, in a paper on "Metallography and the Hardening of Steel," read before the International Engineering Congress in San Francisco, Professor Albert Sauveur made the following remarks:

"It will likewise be obvious that no theory so far presented fully satisfies our craving for a scientifically acceptable explanation of the many phenomena involved. It would seem as if the methods used to date for the elucidation of this complex problem have yielded all they are capable of yielding, and that further straining of these methods will only serve to confuse the issue. . . . The conclusion seems warranted that new avenues of approach must be found if we are ever to obtain a correct answer to this apparent enigma." The author's paper, based as it was on the recent researches on non-ferrous metals conducted mainly in the National Physical Laboratory and at the Bureau of Standards in America, undoubtedly explored a new and fruitful avenue of approach.

If the author's paper were taken conjointly with the memoir by Zay Jeffries and Archer on "The Slip Interference Theory of the Hardening of Metals,"<sup>1</sup> and also with Carl Benedicks' observations on hardening and slip,<sup>2</sup> it became apparent that the general trend of scientific thought lay with the view that hardness was mainly due to the interference with slip and, as the author put it, "Neither an exceedingly hard allotropic variety of iron nor an adamantite iron-carbon compound are necessary" for the explanation of the hardness of hardened steel.

According to Jeffries, "In a pure metal the most simple source of increased hardness is grain refinement, which introduces slip interference at the grain boundaries"; he also introduced the idea of "key-action" by small hard particles, and says that: "Effective hardening is obtained by slip interference within the grains, due to the presence of hard constituents uniformly distributed in the form of very fine particles." The hardness of martensite was explained by Jeffries as follows: "Martensite consists of a solid solution of carbon in very

<sup>1</sup> *Chemical and Metallurgical Engineering*, 1921, vol. xxiv. pp. 1057-1067.

<sup>2</sup> "On the Cooling Power of Liquids," *Journal of the Iron and Steel Institute*, 1908, vol. lxxvii. See also by the same author, *Revue de Métallurgie*, 1922, vol. xix. pp. 505-513, and "Beiträge zur Kenntnis der Elektrizitätsleitung in Metallen und Legierungen" (Aachen, 1916). [*Jahrbuch der Radioaktivität und Elektronik*, vol. xiii., H. 4, pp. 351-395. See p. 390 on "Key-action."



fine-grained alpha-iron. The hardness is due chiefly to the grain refinement of ferrite, but partly to the carbon in solution."

Thus the problem of the hardness of quenched steel was considered from the general point of view of grain refinement and of key-action, but from that standpoint only. The special problem offered by the martensitic structure, and the extraordinary large increase of hardness in it, were not specially dealt with.

Dr. Rosenhain took a general view of the problem when he said that, "Hardening is due to the decomposition of a supersaturated or metastable solid solution obtained by quenching, such decomposition resulting in the production of a very large number of minute crystallites of one or more phases, either constituting the whole of the hardened material or scattered through a crystalline matrix" (p. 160). He (Dr. Rosenhain) also linked up the decomposition of the metastable solution with interference with slip, by saying that "any disturbance of the regular crystalline arrangement results in a corresponding increase of resistance to slip, and, therefore, increase of hardness." But, on the other hand, Dr. Rosenhain was fully alive to some peculiarities in the properties and in the structure of hardened steel; therefore he dwelt at some length on "one outstanding feature in the micro-structure of hardened steel which is not immediately accounted for by the explanation put forward. This is the well-known acicular structure of martensite" (p. 159). However, in what followed the author did away with that peculiarity of the ferrous alloys by saying that martensite was not necessarily hard, and concluded that martensite was "associated primarily with the allotropic transformation of iron and only indirectly connected with the hardening process itself" (p. 160). That point, however, seemed to him (Colonel Belaiew) of particular importance, and he wished to submit the following considerations and suggestions.

As he had stated above, and explained in his contribution to *Chemical and Metallurgical Engineering* on the slip interference theory, he was in agreement with the general conclusions of the author that grain refinement and (with Jeffries and Benedicks) that key-action might be and was productive of an increase in hardness either in ferrous or in non-ferrous alloys. Where he found some difficulty in following the author up to the logical end of his conclusions was in admitting that such a large and sudden increase in hardness, as in quenched steels, was due only and wholly to grain refinement, or even to grain refinement and key-action. If it were so, some of the sorbites ought to have a hardness number equal to that of corresponding quenched steels; but that seemed contrary to fact. Therefore he was inclined to uphold his former views—that a certain and always considerable amount of the increase in hardness was due to the process peculiar to the iron-carbon alloys, namely, the allotropic change from gamma- to alpha-iron. Further, he believed that that change resulted in the martensitic structure, which, in his view, was

a Widmanstätten structure pure and simple; and, finally, that the occurrence of the martensitic-Widmanstätten structure during quenching produced a vast amount of deformation—exhausting, so to speak, to a very large degree the latent possibilities of internal slip in any and every austenitic grain, thus interfering with a further possibility of slip and bringing about a considerable increase of hardness.

It seemed to him that the close analogy between the “acicular” structure of martensite and the Widmanstätten structure had often been overlooked or, at any rate, not sufficiently emphasised. By calling the martensite deposits “needles” a further point of contact with the characteristic shape of the Widmanstätten deposits was lost sight of. Some time ago Benedicks quite rightly pointed out that as the so-called “needles” appeared as such on every section they, after all, could not be needles at all, and must be considered rather as being like plates or lamellæ. On the other hand, a closer scrutiny of martensite samples<sup>1</sup> showed that most of the sections exhibited not three directions, as was sometimes supposed, but four, as befitted a general octahedral section.

The following facts were therefore to be assembled for simultaneous examination :

1. The change from gamma- to alpha-iron during quenching.
2. The simultaneous occurrence during quenching of the Widmanstätten structure.
3. The sudden and large increase of hardness in quenched specimen.
4. The influence of the carbon content on the degree of hardness in quenched specimen.

The allotropic change from gamma to alpha iron during quenching involved a change of volume, as the face-centred cubic arrangement of gamma-iron had to reshape itself into the cube-centred alpha arrangement. As the recent investigations of Westgren had shown, that after quenching at least the major part of iron was in the alpha state, the change in volume must be considerable. Furthermore, that increase of volume occurred in every austenite grain, in every, so to say, point of every grain, and in a very short space of time. It followed that the resulting internal stresses would also occur simultaneously and almost instantaneously in every point of the quenched specimen. The rigidity of the cooled specimen would prevent any considerable adjustment of the grains or of their parts to those stresses after quenching. The resulting structure would have lost a considerable amount of its former ductility and the material would become hardened. The actual process leading to hardening might occur somewhat in the following way.

<sup>1</sup> See, for instance, photograms 2-8 of Carl Benedicks and Eric Walldow's paper, “Röranda martensitens Konstitution ets,” 1918, *Bihang till Jernkontorets Annaler*. Heft. 6.

The change from the gamma to the alpha state occurred simultaneously in every grain. The space of time allotted to that change was very short, but still it might be expected that that change would be gradual; the regions where the change occurred first would appear as "blocks" or "plates," and those would gradually fill the whole or a part of the austenite grain. Owing to the speed of the process, the separation of alpha-iron could not occur mostly or only at the boundaries, and necessarily would occur inside the grain.<sup>1</sup> As the matrix was face-centred, the gliding planes were those of the octahedron, and the first deposits of alpha symmetry would lodge themselves parallel to the four pair of faces of the regular octahedron, thus giving the Widmanstätten figures of the acicular martensitic structure.

The increase of volume caused by the appearance of the first "blocks" or "plates" would cause the occurrence of stresses; those in turn would cause gliding on the octahedral planes and, finally, the appearance of twinned lamellæ at the intersection of every pair of planes, as suggested by Thompson and Millington, thus leading to the Carpenter and Edward "twinned martensite."

The simultaneous appearance of blocks or plates of cube-centred symmetry in every austenitic grain, the resulting gliding on various octahedral planes, and the consecutive appearance of areas of twinned material, would lead to the decrease of the possible amount of further deformation or further potential slip; the material would be hardened. The increase of hardness thus produced might account for the difference in hardness between a martensitic and a sorbitic specimen of the same grain-size.

As the influence of carbon seemed to be to retard the transformation from gamma- to alpha-iron, he (Colonel Belaiew) suggested that the larger the carbon content the smaller would be the time available for the transformation at any given rate of quenching, and, consequently, the more sudden the separation of alpha-iron and the formation of the martensitic structure, and the greater the hardness.

In concluding he wished to take the opportunity of stating that recent work on the structure of austenite and martensite had convinced him of the correctness of Dr. Rosenhain's views on the nature of carbon in solid solution. As previously on many occasions he (Colonel Belaiew) had tried to uphold the "carbide" hypothesis as against that of the atomic dispersion of elementary carbon, he gladly acknowledged his misconception and the truth of Dr. Rosenhain's contention.

Mr. G. R. BOLSOVER (Sheffield) congratulated the author on putting forward a rational explanation of the hardening of steel, which

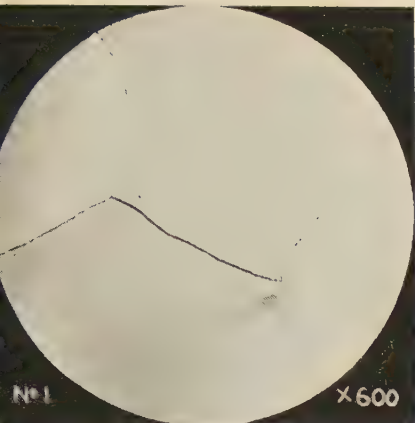
<sup>1</sup> "On the Genesis of Widmanstätten Structure," by Colonel N. T. Belaiew, *Mineralogical Magazine*, 1924, vol. xx. pp. 173-185.

in general would be accepted by most people, although the suggestions in detail were still matters for discussion. In principle the theory was that of "slip interference," as put forward in America by Jeffries, a theory which probably has more in its favour than any other which had been put forward for the explanation of the hardening of metals in general, and of steel in particular. As regarded the detail of the explanations put forward, Dr. Rosenhain stated on p. 159, "On the basis of the views just explained, fully hardened steel (martensite) consists of a mixture of excessively finely divided ferrite and cementite." Why ferrite and cementite? That alpha-iron was present was evident, but that cementite was one of the constituents was by no means established. If such were the case it would be expected, with steel of a given composition, say for simplicity 0.9 per cent. carbon, that, as the speed of cooling from above the change was reduced, there would be increasing opportunity for coagulation of the cementite particles with a corresponding decrease in resistance to slip, and a resultant gradual decrease in, for instance, Brinell hardness values. Such was not the case, as it was found that for the steel in question a perfectly quenched sample would give Brinell hardness of 650 to 700 (according to the method of determining the hardness), and with a reduction in the cooling velocity there was no change in that hardness value until troostite was obtained, when the Brinell value dropped suddenly from the former figure to 450. That suggested a fundamental difference in condition between martensite and troostite, and he (Mr. Bolsover) would suggest that in martensite there was alpha-iron and carbon, the latter being present in uniform atomic dispersion—or, in other words, the carbon was in enforced solid solution in the alpha-iron. With slower speeds of cooling beyond the critical speeds necessary to maintain the foregoing condition, the carbon combined with some of the iron, forming molecules of iron carbide, and when that condition was reached the steel had been converted into a truly troostitic condition. With still slower speeds of cooling the individual carbide particles would become larger, leaving greater areas of ferrite with a consequent decrease of slip interference, and that is found to be so. Once the troostitic condition was passed, it was possible to have a whole range of hardness values in a quenched specimen from 450 Brinell downwards.

With the above explanation it was difficult to see how Dr. Rosenhain would account for the lack in quenched samples of a condition of steel intermediate between that of martensite and troostite.

Sir ROBERT HADFIELD, Bart., F.R.S. (Past-President), wrote that the paper on "The Hardening of Steel" by Dr. Rosenhain appeared to him to be one of the most important papers with regard to the physical condition of steel which had come before the Institute for some time past. He had been specially interested in the conclusions reached on pp. 159 to 161. As Dr. Rosenhain rightly claimed, there was no doubt





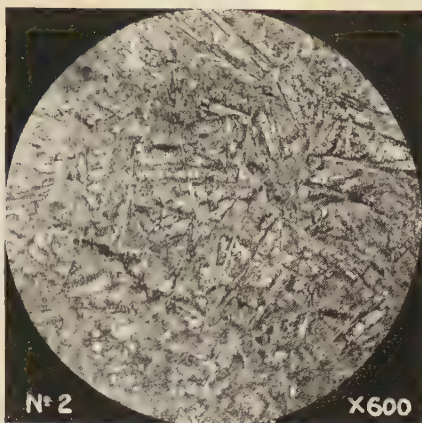
No. 1

Composition : 1·16 per cent. C., ·34 per cent. Si., 12·36 per cent. Mn.

Water quenched from about 1000°C.

Austenitic structure :

Yield Point, 24 tons per sq. inch ; Tenacity, 67 tons per sq. inch ; Elongation, 65 per cent. ; Reduction of Area, 45 per cent. ; Ball hardness No., 200. Specific magnetism : under ·20 per cent.



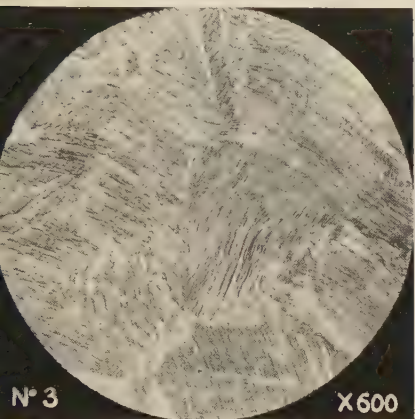
No. 2

Composition : 1·26 per cent. C., ·32 per cent. Si., 13·38 per cent. Mn.

Water quenched from about 1000°C. ; reheated to 500°C. for 60 hours ; cooled slowly in furnace.

Acicular structure :

Tenacity : under 30 tons per sq. inch ; Elongation, practically nil ; Ball hardness No., 444, in some cases over 500. Specific magnetism : 41·00 per cent.



No. 3

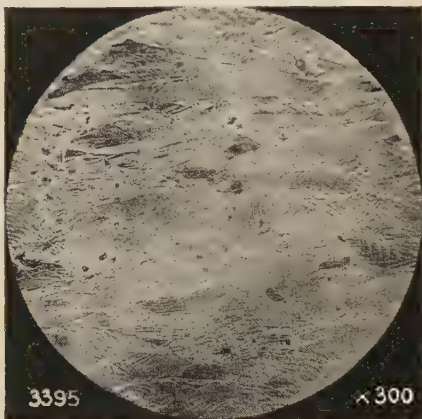
Composition : 1·23 per cent. C., ·27 per cent. Si., 12·98 per cent. Mn.

Water quenched from about 1000°C.

Old worked by straining in testing machine. Much-distorted austenite :

Yield Point, 27 tons per sq. inch ; Tenacity, 67 tons per sq. inch ; Elongation, 74 per cent. ; Reduction of Area, 47 per cent. ; Ball hardness No., 235 before testing, 512 after testing.

Specific magnetism : under ·10 per cent. before testing, about ·30 per cent. after testing.



No. 4

Composition : 1·36 per cent. C. ; ·29 per cent. Si. ; 13·00 per cent. Mn.

Compression piece ·7979 inch diameter, 1 inch in length.

Water quenched from about 1000°C.

Much-distorted austenite :

Ball hardness No., 214 before compression, 555 after compression with 400 tons per square inch ; 570 in one portion of specimen.





that fully hardened steel consisted of iron and carbide in an exceedingly fine state of division, or as termed by him, "excessively finely divided ferrite and cementite." Dr. Rosenhain went on to say that that explanation did not immediately account for the well-known acicular structure of martensite. He instanced structures which were hard but not acicular, and others which were acicular but not hard. Dr. Arnold had stated that properly hardened carbon steel was structureless under the microscope. Hence he (Sir Robert) could fully agree with Dr. Rosenhain's statement that "the connection between a martensitic structure and extreme hardness is perhaps rather accidental than causative," that was, if the word "acicular" was substituted for "martensitic."

There were several points in relation to the structure of hardened steel about which he wished to ask the following questions, as they seemed to him to bear upon the main subject under consideration.

In manganese steel which was heated to 500° C. for about sixty hours, a martensitic structure was produced and the material became magnetic; in some cases its specific magnetism as compared with pure iron was as much as 50 per cent. Before that treatment the specific magnetism was a mere trace, namely, 0.10 per cent., or even less. The Brinell ball hardness rose from about 200 in the non-magnetic to 444 in the magnetic condition. A paper entitled "The Magnetic and Mechanical Properties of Manganese Steel" was read before the Institute by the late Professor Bertram Hopkinson and himself which dealt with that interesting subject. The austenitic structure of manganese steel in the water-toughened condition and the acicular structure obtained by prolonged heating at 500° C. were shown by the accompanying photomicrographs, Nos. 1 and 2 respectively (Plate IX.A).

Now the same manganese steel in its non-magnetic condition and possessing the well-known austenitic structure, after quenching, would have a hardness of about 200 Brinell. Yet the hardness of that material in the form of a tensile test-bar which had been elongated in the testing machine, say 60 per cent. on a length of 4 inches, became increased to no less than 550 Brinell ball number, though the material still remained non-magnetic. There was a slight increase in specific magnetism, namely, to about 0.30 as compared with under 0.10 before being strained by tensile testing. Thus there was obtained a material which was quite as hard as, or even harder than, that produced by heat-treating the same steel at 520° C. A micro-examination showed that the material had not changed its constitution in any way; no new constituent had appeared, but the crystals had simply been disturbed, as shown by photomicrograph No. 3. So far he (Sir Robert) was not aware that a satisfactory explanation had been given for those peculiar results.

It would appear, therefore, possible to raise the hardness of manganese steel from 200 to nearly glass-scratching hardness (about

600) by the two methods just described, one, as the photomicrograph showed, indicating an enormous structural change, whereas in the other there was no change beyond distortion. \*

In considering the variation in hardness capable of being produced in manganese steel by mechanical and thermal treatment, the accompanying photomicrographs (Figs. 1 to 4, Plate IX.A) would appear to be of interest.

Photomicrograph No. 1 represented the standard Hadfield manganese steel, water-quenched from about  $1000^{\circ}\text{C}.$ , and of austenitic structure. The yield point was 24 tons per square inch; tenacity, 67 tons per square inch; elongation, 65 per cent., and reduction of area, 45 per cent.; ball hardness number, 200; specific magnetism practically nil, under 0.20 per cent. Photomicrograph No. 3 represented similar material to No. 1—namely, forged manganese steel, water-quenched from about  $1000^{\circ}\text{C}.$ , and after being cold-worked by straining in the tensile testing machine. The particular test-bar from which that photomicrograph was taken possessed a yield point of 27 tons per square inch, a tenacity of 67 tons per square inch, an elongation of 74 per cent., and reduction of area of 47 per cent.; ball hardness number 235 before testing, and afterwards 512, taken at the fracture; specific magnetism under 0.10 per cent. before testing, and about 0.30 per cent. after testing.

It would be observed that after being strained as above described the material still retained its austenitic structure. Moreover, that structure was not martensitic, the manganese steel lines (to use the late Professor Howe's term) on each grain being due to stress. The specific magnetism remained practically the same as No. 1, that was, non-magnetic, but the ball hardness number had increased to no less than 512.

Photomicrograph No. 2 represented similar material, water-quenched from about  $1000^{\circ}\text{C}.$ , then reheated to  $500^{\circ}\text{C}.$  for sixty hours and slowly cooled in the furnace. It would be noticed that the austenitic structure had entirely disappeared, being replaced by an acicular structure. The steel was now very brittle, with a tenacity of under 30 tons per square inch, practically no elongation, and shock tests showed no bending angle at all. The ball hardness number was 444, and in some cases reached over 500. The specific magnetism had increased from practically nil to 41.00 per cent. as compared with Swedish charcoal iron, 100.00 per cent.

Photomicrograph No. 4 represented a compression piece 0.7979 inch diameter and 1 inch in length of forged manganese steel, water-quenched from about  $1000^{\circ}\text{C}.$  Before compression it possessed a ball hardness of 214, but after compression with 400 tons per square inch its hardness was increased to 555, and in one portion of the specimen to 570 ball hardness number.

The original photomicrographs had been reduced to  $2/3$  linear dimensions in the half-tone reproductions shown.

The following are the exact compositions of the various specimens referred to :

Photomicrograph No.	Carbon.	Silicon.	Manganese.
1	1.16	0.34	12.36
2	1.26	0.32	13.38
3	1.23	0.27	12.98
4	1.36	0.29	13.00

The above results showed that, in manganese steel, it was possible to obtain very great increase in hardness without apparently any chemical or structural change taking place.

Professor KÔTARÔ HONDA (Sendai, Japan) wrote that the theory of hardening put forward by Dr. Rosenhain was a very ingenious explanation of the cause of the hardness of the alloys of the Duralumin type, as well as that of steels. It was interesting to note that his way of explaining the hardening was just the reverse to his (Professor Honda's). Thus while Dr. Rosenhain explained the hardness of steel just as he did the hardening of light alloys, he (Professor Honda) explained the hardening of light alloys in just the same way as that of carbon steels. The essential point of Dr. Rosenhain's theory depended on the nature of the martensite ; according to him, martensite was a decomposition product of austenite, but he (Professor Honda) considered the structure to be a homogeneous substance or phase. From the standpoint of microscopic observation, the martensite consisted of very beautiful needle-shaped crystals and was considered to be a solid solution of carbon in  $\alpha$ -iron. A number of the physical properties of the martensite accorded very well with that view. One important phenomenon to be noticed was the diffusion of the X-ray spectrum lines of martensite. That was usually explained by assuming that each individual needle-shaped crystal consisted of a very large number of minute crystals orientated at random, their linear dimensions containing only several hundreds of atoms. That explanation did not, however, agree well with the result of microscopic observation, but the following new explanation would very probably express the actual fact.

Owing to a very rapid cooling, the martensite structure underwent a great internal stress ; a number of martensitic crystals were in a state of tension and numbers of others in a state of compression (not only hydrostatic tension or compression, but also simple tension or compression), their intensities varying from crystals to crystals. Shear being considered as made up of tension and compression, did not require special consideration. Hence in certain groups of crystals the lattice distance increased in one direction and decreased in the perpendicular direction, and in other groups it was uniformly increased

or decreased; the amount of those changes depended on the intensity of stress, being of the order of  $\frac{1}{1000}$  of the lattice distance. There were also many groups of crystals whose lattice constant remained unchanged. When such an aggregate of minute crystals was examined by the X-ray, it was to be expected that the spectral lines would be of a diffused nature. Thus the diffusion of spectral lines was satisfactorily explained by the deformation of the space-lattice by stress, and hence there was no need of assuming a very finely dispersed structure of the martensite. According to the above explanation, from the maximum range of the diffusion the maximum stress could be estimated. Taking the maximum diffusion of the lines to be  $\frac{1}{1000}$  of the lattice-distance, the intensity of the internal stress was found to be about 20 kg./mm.<sup>2</sup>, which was of the right order of magnitude. It could thus be safely concluded that the martensite consisting of very well-defined crystals was not a decomposition product, but a definite homogeneous phase, being a solid solution of carbon in  $\alpha$ -iron, and consequently that Dr. Rosenhain's extension of the hardening theory of light alloys to the case of steels did not hold good.

Dr. Rosenhain explained the hardness of the martensite by the slip-interference on the boundaries of individual crystals. According to his (Professor Honda's) opinion, crystal boundaries had no very different properties from the crystals themselves, and hence the slip, although somewhat difficult across the boundaries, was not, obviously, impossible. The fact was that across the boundary the directions of the slip-planes generally changed as the direction of the space-lattice was different for different crystals, and hence the slip was more or less prevented by the boundary. So although the increase of the hardness of a certain amount was to be expected, the great hardness of the martensite could not be explained by the presence of the large number of boundaries of minute crystals, unless some special assumption were made as to the nature of the boundaries, such as an amorphous layer possessing an enormous specific strength, an assumption which was very improbable. Hence an attempt to explain the great hardness of martensite slip-interference on the boundary seemed to him untenable.

In regard to the hardening of the alloys of Duralumin type, here again the main point of dispute was whether the aged Duralumin was the decomposition product from a solid solution or not. There was no direct proof of the decomposition product; the fact was that if it were assumed that the ageing of Duralumin was due to the precipitation of a compound  $Mg_2Si$  from the solid solution and that that dispersed substance was very hard, the hardening phenomenon could be satisfactorily explained. It was, however, known, as an experimental fact, that the ageing was not due to the precipitation of the compound; because, as was found by Dr. S. Konno<sup>1</sup> during the precipitation of the compound by tempering, the electric resistance decreased, but, on the contrary, during ageing, the resistance continuously increased.

<sup>1</sup> S. Konno, *Japanese Report*, 1920; *Science Reports*, 1922, vol. xi.



Hence so long as a direct proof of the precipitation theory was not given, he could not admit the explanation as given by Dr. Rosenhain. The hardening effect of the alloys of the Duralumin type could be satisfactorily explained without taking account of the precipitation theory.<sup>1</sup>

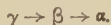
Since the hardening phenomena of Duralumin were similar to those of carbon steels, they could be explained in a similar way. The solubility of  $\text{Mg}_2\text{Si}$  in aluminium increased rapidly with the temperature, but the dissolution or precipitation went on very slowly. Hence a greater part of the dissolved  $\text{Mg}_2\text{Si}$  above  $500^\circ\text{C}$ . precipitated or separated out by a very slow cooling; but by a rapid cooling the precipitation was arrested. The precipitation consisted of the change:



or simply expressed,



Since  $\text{Mg}_2\text{Si}$  was atomically dispersed in the solid solution of aluminium, its separation was not easy; hence it might properly be assumed that the distribution of manganese and silicon atoms in the solid solution of aluminium was first changed into a less stable configuration which was more favourable to the separation of manganese and silicon atoms as  $\text{Mg}_2\text{Si}$ , and then the precipitation followed. That less stable or metastable configuration of manganese and silicon atoms in the solid solution was called  $\beta$ ;  $\beta$  was a solid solution and corresponded with the martensite in the case of steels, and was assumed to be much harder than  $\gamma$  or  $\alpha$ . The process of precipitation consisted therefore of the changes:



According to the above view, by quenching Duralumin in water, even the first change,  $\gamma \rightarrow \beta$ , was partially arrested, and  $\beta$  was obtained mixed with  $\gamma$  at room temperature. The  $\gamma$  thus arrested changed, at room temperature, very slowly into a hard solid solution  $\beta$ ; but  $\beta$  changed but very little into  $\alpha$ . The consequence was that by quenching the alloy was hardened, and its hardness increased with time. Thus the immediate effect of quenching was determined by the quantity of  $\beta$  present, and the ageing effect by that of  $\gamma$  arrested.

If the quenching were very severe, a large part of  $\gamma$  was present at room temperature, only a small remainder being  $\beta$ , so that the immediate hardening effect was small, but the ageing effect was very large. As the quenching became less drastic, the quantity of  $\beta$  at room temperature increased and that of  $\gamma$  decreased, so that the immediate effect increased, but the ageing effect decreased. By heating the quenched specimen a little, say to  $100^\circ$ , the change of the arrested  $\gamma$  into  $\beta$  was accelerated, so that the ageing took place in a comparatively short time, as actually observed. But if the heating

<sup>1</sup> S. Konno, *Loc. cit.*

temperature were too high, say  $300^{\circ}$  to  $350^{\circ}$ , not only the arrested  $\gamma$  changed into  $\beta$ , but also the second change,  $\beta \rightarrow \alpha$ , took place comparatively rapidly, owing to the diminution of viscosity, so that the hardness decreased as a whole. That was the case in tempering Duralumin.

The compound  $\text{Al}_2\text{Cu}$  in Duralumin behaved also in a similar way, but to a less marked degree.

With regard to the specific resistance  $\sigma$  of  $\alpha$ ,  $\beta$ ,  $\gamma$ , in conformity with the experimental fact, it was assumed that

$$\sigma_{\alpha} < \sigma_{\beta} > \sigma_{\gamma}.$$

The fact that during the ageing of the quenched Duralumin the specific resistance increased was a consequence of the gradual change of arrested  $\gamma$  into  $\beta$ .

In the reheating curve of specific resistance or thermal expansion of a quenched Duralumin, two slipped abnormal changes were observed at  $210^{\circ}$  and  $280^{\circ}$ . Those changes were due to the separation of the compounds  $\text{Mg}_2\text{Si}$  and  $\text{Al}_2\text{Cu}$  respectively from the aluminium solid solution during tempering.

~~As~~ Taking another case of an alloy of aluminium-zinc considered by Dr. Rosenhain (pp. 153-156 in his paper), according to the above view, the microstructure in Fig. 4, Plate IX., in his paper was the  $\gamma$  phase ( $= \beta$  in his notation), and in Fig. 6 the white areas were  $\beta$  in his (Professor Honda's) notation (not  $\beta$  in Dr. Rosenhain's notation), which was changed from  $\gamma$ , and the dark areas the decomposed product  $\alpha$  (in his, Professor Honda's, notation), just like troostite or sorbite in the case of carbon steel. With the lapse of time, owing to the progressive decomposition of  $\beta$  (not  $\beta$  in Dr. Rosenhain's notation), dark area increased at the cost of white area. The  $\beta$  being harder than  $\gamma$  and  $\alpha$  (Professor Honda's notation), it was to be expected that the hardness of the quenched alloy showed first increase, reach a maximum, and then decrease.

The above explanations were given by way of examples; but all the results cited by Dr. Rosenhain could be equally well explained by the above theory.

Professor F. C. THOMPSON (Manchester) wrote, Dr. Rosenhain's paper divided itself into two distinct portions. In the first place, he had attempted to draw attention to the similarities which existed between the age-hardening of Duralumin and other alloys and the hardening of steel, thus linking up ferrous and non-ferrous metallography. To a considerable extent his conclusions appeared to be justifiable, and good service to metallurgy had been done. The second part of the paper dealt with Dr. Rosenhain's views of the constitution of martensite, and it is with that section that he (Professor Thompson) wished particularly to deal.

Those views appeared to have had their basis in Dr. Rosenhain's

conception of the mechanism of the age-hardening of the Duralumin, and it was therefore of interest to consider how far those ideas could legitimately be accepted. It was admitted by the author on p. 150 that no evidence had yet been obtained that during that ageing anything was actually precipitated from the solid solution, and the statement, therefore, that the particles which were believed by him to be so thrown out of solution must be of ultra-microscopic dimensions was distinctly weak. It was also possible that no microscopic change was detected, because there was none to detect. In other words, that the changes in properties during ageing were not due to any precipitation, but to the development of internal stress. There was very direct evidence that the latter view was the more accurate. If, as Dr. Rosenhain assumed, magnesium silicide was thrown out of solution during ageing, there should be a marked drop in the electrical resistivity. Konno had shown, however, that during the process the resistivity, so far from falling, as it would do if Dr. Rosenhain was correct, actually showed a distinct increase. That fact was in absolute opposition to Dr. Rosenhain's views, but it explained why no structural change was to be detected.

In the hardening of steels there was equally good evidence that no precipitation of carbide occurred, and thus that the formation of martensite was not the result of the operations which were suggested in the paper. Both in plain carbon and in alloy steels it had been shown that in martensite the resistivity was that compatible with the view that the carbide existed still in an extremely supersaturated solution in  $\alpha$ -iron. If that were so, then the hardening of steel was not due to the process suggested by the author, but again to the production of internal stress. Further, if Dr. Rosenhain's views were to be adopted, they would involve the assumption of a structure for martensite which was identical with that at present believed to be that of troostite, and that would entail discovering, for the latter constituent, some entirely new constitution, which would be the more deplorable, since the whole of the known properties fitted in so well with the idea that it did consist of—as Arnold called it—an emulsified pearlite, or, in Benedick's terms, a colloidal solution of carbide in  $\alpha$ -iron. The constitution of martensite as Dr. Rosenhain saw it was exactly the constitution of troostite as all the work so far done revealed it.

There was another aspect of the theory which Dr. Rosenhain propounded which he might consider. It was clear from the results of several workers that the tempering of martensite was not a continuous process, but took place in two distinct stages. It would be of interest if Dr. Rosenhain would indicate how that was possible on the lines of his theory. It was true that the ageing of Duralumin could also be shown to take place in two stages, but the evidence was good that that arose from two distinct precipitations, one of  $\text{Mg}_2\text{Si}$  and the other of  $\text{CuAl}_2$ .

A further serious weakness in the argument that the hardening of

steel and of the non-ferrous materials followed the same lines arose from the absence of a "martensite" in the Duralumin. Structurally, austenite, martensite, and troostite were perfectly distinct and readily detected microscopically. In the whole of the non-ferrous alloys so far examined two constituents only could be seen—the analogues of austenite and troostite. The martensite stage was always microscopically absent, and an attempt to explain the hardening of steel from analogies in which the martensite stage was non-existent was clearly unsatisfactory. The argument used in the paper that, since other non-ferrous materials showed a martensitic structure, the existence of that in the non-ferrous materials was proved was very weak. It would be agreed that a structure analogous to martensite could be seen in many non-ferrous metals and alloys. Pure zinc showed it clearly, as would be seen from the illustration in Smith's book on that metal. Quenched Muntz metal also showed it extremely well, but those facts would not appear to be of much use to Dr. Rosenhain. To substantiate his theory it was clearly necessary that he should be able to show that those materials which showed hardening effects should also show a "martensite" themselves as an intermediate product between the "austenite" and the "troostite." That he had failed to do.

He (Professor Thompson) was forced to conclude, therefore, that martensite had not the structure ascribed to it by Dr. Rosenhain, nor was its hardness to be explained in the way he assumed.

There was one other point of detail to which attention should be drawn. On p. 159 the author stated that "here the whole of the  $\gamma$ -iron solid solution undergoes transformation." That might be Dr. Rosenhain's view, but it would have been better had the statement been made in a somewhat less dogmatic fashion. It was, to say the least of it, very far from certain that all the  $\gamma$ -iron had been transformed. To take one example only, there was very real reason to believe that the sole object of ageing a magnet steel was to cause the transformation of the residual  $\gamma$ -iron in the martensite.

To say, therefore, as the author did, that "a large amount of new light has undoubtedly been thrown on the subject" was open to serious criticism. To him (Professor Thompson) the position stood exactly where it had done before, and the paper afforded no adequate reason for the alteration of his view that martensite was an extremely super-saturated solid solution of iron carbide, with possibly dissociated carbon in  $\alpha$ -iron, together with an indeterminate amount of unchanged  $\gamma$ -iron, the hardening being due to the formation of internal stresses and not to any precipitation of carbide from solution.

Mr. J. H. WHITELEY (Saltburn) wrote that although Dr. Rosenhain had shown in his usual clear and forceful manner the close similarity that existed between the behaviour of certain alloys and steel on quenching, he (Mr. Whiteley) thought that he was in danger of confusing martensite with troostite. It was now generally accepted that troostite



consisted of an exceedingly fine mixture of  $\alpha$ -iron and cementite. Indeed, strong proof of that was afforded by the fact that it stained with sodium picrate which, as far as he (Mr. Whiteley) had observed, true martensite failed to do. If, as Dr. Rosenhain maintained, martensite was also simply a mixture of  $\alpha$ -iron and cementite, then, since troostite was similar in character, the transition from the one to the other should surely be gradual, which was by no means the case. There was always a clear line of demarcation between the two on the etched surface, a feature which did not seem to accord well with Dr. Rosenhain's explanation of martensite. On the other hand, between troostite and sorbite that abrupt change was much less pronounced, as might be expected, since both were mixtures of the same constituents. It would be very interesting to have Dr. Rosenhain's views on the nature of troostite from the standpoint of the theory he had advanced in his paper.

Dr. W. ROSENHAIN, F.R.S. (Teddington), wrote, in reply to the above correspondence, that in a reply of reasonable length it was difficult to deal with the large number of points which had been raised. He (Dr. Rosenhain) was not surprised to find that a number of metallurgists adhered to the older views on the hardening of steel with remarkable tenacity. The newer and more generalised views which he had put forward would necessarily take time to carry the conviction to which he believed they were entitled. Curiously enough, however, there was no unanimity among those who attacked his (Dr. Rosenhain's) views as to the proper alternative theory, each contributor to the discussion advancing different and incompatible views. Dealing with those in turn, Colonel Belaiew, like several of the other writers, could not accept his (Dr. Rosenhain's) view of the nature of martensite. Colonel Belaiew apparently adhered to the older view that martensite was largely a product of twinning, although he admitted, in view of the indisputable X-ray evidence, that  $\alpha$ -iron was present. It might be pointed out that it was not necessary, in connection with the theory put forward in the paper, to come to any decision as to whether or not twinning played a part in the production of the martensitic structure. The main point, however, was that twinning alone could not possibly account for the hardness of martensite. Copper which had been cold-worked and annealed was very freely twinned, but was, if anything, rather softer and not harder than before. There was, in fact, no evidence that the existence of twinned formation tended to harden the material. If twinning did not contribute to hardness, on the view put forward by Colonel Belaiew, it would have to be ascribed to internal stresses. On that point it had to be remembered that a change of volume which occurred simultaneously, or almost simultaneously, throughout a mass of metal, need not, and, in fact, could not, give rise to any system of internal stresses. Such stresses only arose when portions of a mass underwent change of volume, and that change was resisted by other portions which had not undergone any change. If



the hardness of steel were so closely connected with the production of internal stresses, larger masses of steel would be more readily and fully hardened than very minute ones. None the less, full hardness could be obtained more readily in the finest wire in which the existence of stresses due to differential expansion could scarcely be assumed. There was also the further argument that the transformation described by Colonel Belaiew must occur at least as completely in pure iron as in a carbon steel; yet, as was well known, pure iron underwent no appreciable hardening by quenching.

Mr. Bolsover began by suggesting that in principle the theory put forward in his (Dr. Rosenhain's) paper was the "slip interference" theory of Jeffries. While by no means anxious to raise any questions of priority, particularly in connection with Dr. Jeffries, with whom he (Dr. Rosenhain) maintains the most friendly relations, he would point out that Jeffries' contribution to that theory consisted mainly of a clear and more detailed restatement, under a new name, of views originally put forward by Beilby. Beilby's views had been further elaborated in the present paper, and Jeffries' contribution only came at a much later stage. There was, however, one important point upon which the theory put forward in the present paper differed from that of slip interference as enunciated by Jeffries. In Jeffries' view, interference with slip was due to the presence, on or among the slip planes, of hard particles which acted as keys. In his (Dr. Rosenhain's) view the presence of actual *hard* particles was by no means essential, and would not, in fact, be efficient for such a purpose. The interference with slip, according to the present view, was due not to any key action or to the presence of *hard* particles, but to general disturbance of the lattice structure resulting in an increased resistance to slip which might, in the last resort, amount to the complete inhibition of slip and, therefore, of plasticity. Although that might at first sight appear to be a difference in detail, it materially affected the general character of the theory.

Mr. Bolsover next raised the question why it should be supposed that martensite was a mixture of ferrite and cementite. That ferrite or rather alpha-iron crystals were present was regarded as established on X-ray evidence obtained by Westgren and others. The actual presence of cementite was not so certain, since it had not been established by X-ray evidence or other direct means. On the other hand, it could be shown that there was every reason to think that that substance must be present in those conditions. Both Mr. Bolsover and Professor F. C. Thompson considered that martensite was a highly supersaturated solid solution of carbon in alpha-iron. He (Dr. Rosenhain) thought it could be clearly shown that the formation of such a solid solution was a theoretical impossibility, and that the evidence cited in its favour was open to other and more rational explanation. When steel was cooled either slowly or quickly from a high temperature it underwent certain transformations, and there could be no doubt that those transformations took place, because they

involved a liberation of energy. The liberation of that energy could actually be observed even in quenched steel. In those circumstances it followed that the product of such transformation must have a lower energy content than the phase from which it had been formed. The energy content of a saturated solid solution was such that if it were exceeded in the least degree, other arrangements of the atoms could be found having a lesser energy content. It was, in fact, that condition which determined the limit of saturation. In the case, therefore, of a phase A undergoing transformation, and such a transformation taking the form of a change into a solid solution B, or a mixture of two different bodies C and D, if the concentrations were such that the resultant solid solution B was not saturated, it might be expected that that solid solution would be formed, since the incompletely saturated solid solution B would have a lower content of energy than the mixture of C and D. On the other hand, a supersaturated solid solution B would have a higher content of energy than a mixture of C and D. If at a high temperature a saturated or under-saturated solid solution B could be formed which became supersaturated by cooling, it might persist in a metastable stage. It would, however, seem to be inconceivable that when a transformation from the state A occurred that should result in the formation of a supersaturated solid solution having a higher energy content than a mixture of two other phases. That led to the conclusion that a supersaturated solid solution of carbon in alpha-iron could not, on thermo-dynamic grounds, be formed as a transition or transformation product in preference to a mixture of alpha-iron and cementite. One reservation, however, needed to be made in that connection. There was no available evidence that the carbon separated from solid solution in gamma-iron *immediately* took the form of the compound  $\text{Fe}_3\text{C}$  either molecularly or in a crystalline aggregate. It would be equally consistent with the views he (Dr. Rosenhain) put forward if martensite consisted of crystals of alpha-iron with more or less uncombined carbon scattered through it in the form of separate particles. The essential point was that the crystallites of alpha-iron themselves must be extremely minute, and that the disturbing particles of a second phase must also be excessively minute and scattered through the alpha-iron crystallites in such a way as completely to disturb the slip mechanism. It was quite possible that the transition from martensite to troostite, which was known to be somewhat abrupt, might be associated with a transformation in the condition of the carbon. There was no evidence upon which to base a view of that kind, except the mere fact of a somewhat sudden transition. Such a transition, however, might very well be accounted for by a change in the size of the dispersed particles whose influence on the properties of the mass might reach a critical value for a given size of particles. While in his (Dr. Rosenhain's) opinion the hypothesis of the existence of supersaturated solid solution of carbon in alpha-iron had been fully disproved by the argument advanced above, there was a further piece

of direct evidence. The fact that Westgren found by X-ray measurements in martensite the lattice of alpha-iron differing only from the lattice of alpha-iron as observed in that metal at the ordinary temperature by an amount corresponding to the thermal expansion of the metal, indicated that there could not be any large amount of any other element present in the alpha-iron of martensite. The presence of carbon in solid solution in a state of high supersaturation must inevitably change the lattice constant of the alpha-iron to an extent which Westgren could not have failed to observe. There was thus direct experimental evidence against the assumption of the existence of such a supersaturated solid solution.

It was rather more difficult to deal with Professor Honda's remarks. His views were based upon an assumption for which there did not appear to be the slightest degree of experimental evidence, namely, that there was an actual intermediate phase, both in the iron-carbon system and in the aluminium alloys, which was inherently hard. Professor Honda suggested no explanation for the supposed hardness of such an intermediate phase, and was unable to assign to it a definite constitution, a definite place on an equilibrium diagram, or an ascertained X-ray lattice structure. In the absence of any such facts it was scarcely necessary to take such an assumption seriously. It was little more than an unsupported statement of an opinion which could make little appeal to metallurgists accustomed to reasoning upon accurate data. One point which Professor Honda raised, and which was also referred to by other contributors to the discussion, was the fact that it had been shown by Konno that during the age-hardening of Duralumin the electrical resistivity increased instead of decreasing, as Professor Honda suggested that it should. That was a point of some importance and would require to be dealt with in detail.

That the deposition of a separate phase from a solid solution led to a reduction in the electrical resistance was, in general terms, admittedly correct. Before it could, however, be applied to the very special case of decomposition which occurred in the case of hardening, the mechanism of what occurred would have to be more carefully investigated. He (Dr. Rosenhain) had recently pointed out (May Lecture to the Institute of Metals, 1923), and it had previously been pointed out by Lindemann, that the high electrical resistivity of solid solutions was due to the distortion of the space lattice of the metal crystals by the presence in them of stranger atoms. That distortion increased with increasing concentration of the solid solution, and if anything occurred to diminish the concentration of such a solid solution the electrical resistance would also diminish. It must, however, be realised that that state of affairs could only arise if the crystallisation of the solid solution, whether saturated or under-saturated, was substantially undisturbed. It was only in such circumstances that a regular space lattice could develop itself freely, and that the reduced electrical resistivity of the less concentrated solid solution could make



itself felt. When a solute was deposited in the form of separate crystals during slow cooling or annealing, those circumstances were fulfilled, and accordingly the well-known series of phenomena were found. It was, however, entirely unjustifiable to conclude that in other circumstances where the recrystallisation of the solid solution from or in which deposition of a separate phase was occurring was seriously hindered or prevented, similar results would follow. On the contrary, if the view of the hardening of metals by the decomposition of a supersaturated solid solution which had been put forward in the paper was correct, the rectilinear space lattice arrangement of the atoms of the solid solution, already partially disturbed by the pressure of the solute atoms, would be much more seriously disturbed and, in fact, to a large extent destroyed by the deposition of a very large number of minute crystallites of the new phase separating during the hardening process. In those circumstances the passage of electrons through or between the atoms would be more completely hindered in the decomposed solid solution than it was before such decomposition took place, and accordingly, during the hardening process, so long as the disturbance in the lattice structure increased with further deposition, so long would the electrical resistance increase also. It would, therefore, be expected here, as indeed everywhere, that mechanical hardness and electrical resistance would go together. If those views were correct and an understanding of the inner structure of metals and alloys had now progressed to such a stage that it was possible to argue upon them with confidence—then the arguments used by Professor Honda and others from the increase of electrical resistance during hardening fell to the ground as an objection to the theory he (Dr. Rosenhain) had put forward. That phenomenon was, in fact, what that theory would indicate.

Professor Thompson had undoubtedly put his finger upon what would appear at first sight to be a weak spot in the arguments and evidence put forward in favour of his (Dr. Rosenhain's) theory. That was the failure to prove microscopically the existence of minute deposited particles in age-hardened Duralumin or similar alloys. It was obviously always preferable, where it was possible, to give ocular demonstration rather than indirect evidence. On the other hand, a large amount of scientific knowledge related to matters entirely removed from the range of vision, and the mere fact that ocular demonstration could not be given was by no means always a valid objection to the accuracy of theoretical views. He (Dr. Rosenhain) would suggest that the present case was an instance of that kind. There was, in certain aluminium alloys, a continuous series of phenomena resulting ultimately in the deposition of minute, just visible particles of a second phase, such as  $Mg_2Si$  or  $CuAl_2$ . It was not unreasonable to suppose that the continuous phenomenon in question was continuous in that respect also, and that the deposition of the separated phase commenced, as it was bound to commence, in the deposition of ultra-microscopically minute

particles. Beyond that the matter must be treated as an assumption upon which the theory was based, and its proof or otherwise judged by the success of the theory in accounting for the facts with which it was called upon to deal. In the present instance it was suggested that if the facts were rightly viewed there could be little doubt as to the success of the theory. Incidentally, it might be pointed out that none of the other theories hitherto put forward to explain the hardening of steel were free from assumptions at least as difficult of direct proof as the present one.

Several contributors to the discussion raised the question of the exact structure of martensite. Professor Honda appeared to consider that microscopic evidence could be relied upon to show that it did not consist of an aggregate of minute crystals. That could only be regarded as a personal opinion, with which he (Dr. Rosenhain) did not agree. In any case the fact remained that exceedingly hard materials free from martensitic structure existed as well as martensitic structure without hardness, as, for instance, in quenched low-carbon steels. The direct association of the martensitic structure with a particular degree of hardness in a higher carbon steel would, therefore, appear to be accidental rather than causative. That a martensitic structure was in some way connected with allotropic transformation was suggested by its occurrence in other metals than iron which underwent allotropy, while metals free from allotropic transformation did not tend to develop martensitic structure. The very great hardness of martensitic steel and the marked change between martensite and troostite might, however, well be associated with the allotropic transformation of iron itself. It had to be pointed out that the case of carbon steel differed from the non-ferrous alloys described in the paper by the fact that in the former the solubility of carbon in gamma-iron ceased suddenly in consequence of an allotropic transformation, while in the non-ferrous alloys it was a question of diminishing solubility with falling temperature. The transformation and the accompanying disturbance of crystalline structure which occurred at a critical point in steel must therefore be of a much more violent and sudden character than in the non-ferrous alloys in question. As had been pointed out in the discussion, it did not follow that the whole of the transformation was necessarily completed during quenching in the case of a steel. If there were any residual gamma-iron solid solution left either in or mingled with the martensite, its subsequent decomposition might be the determining factor in the transition from martensite to troostite. Apart from such a possible factor, the structural differentiation between martensite and troostite on his (Dr. Rosenhain's) theory became merely a question of the size and arrangement of the particles of carbon or carbide and of the alpha-iron crystallites.

He (Dr. Rosenhain) had been particularly interested in the contribution to the discussion from Sir Robert Hadfield. The behaviour of manganese steel on prolonged tempering and slow cooling, when it



became martensitic and magnetic, was entirely in accordance with what would be anticipated from his (Dr. Rosenhain's) theory. On the other hand, the remarkable effect of cold-working, as evidenced by the properties of a tensile test-piece described by Sir Robert Hadfield, was exceedingly difficult to understand. That difficulty, however, would persist, whatever view of the nature of the hardening of steel were adopted. Manganese steel was a complex alloy whose real nature and constitution was not yet fully understood. Such a full understanding would, however, be necessary in order to account for its behaviour in the special circumstances described by Sir Robert, and a general theory of hardening and tempering could hardly be expected to furnish the whole of such an explanation without a much fuller knowledge of the facts. Those facts, however, were being investigated, at any rate, so far as the alloys of iron and manganese were concerned, at the present time, and it might be hoped that the results of that investigation would ultimately make it possible to explain the remarkably interesting fact described in Sir Robert Hadfield's contribution.



## Iron and Steel Institute.

### IMPROVEMENTS IN THE BRINELL TEST ON HARDENED STEEL, INCLUDING A NEW METHOD OF PRODUCING HARD STEEL BALLS.

BY AXEL HULTGREN, MET.ENG. (GOTHENBURG).

As is well known, in testing hardened steel according to the Brinell method the following difficulties are encountered : (1) The ball, on account of insufficient hardness, is flattened permanently under the load applied ; the impression becomes too shallow and too wide, and in consequence the hardness number, calculated upon the diameter of impression, becomes too small. (2) The impression, on account of its small size and shallowness, is difficult to measure with the degree of accuracy desired.

In consequence this test is practically limited in its use to soft and medium hard metals. If applied to the testing of hardened steel, the hardness number obtained is always too low, and the result should be judged with caution, since the lack of hardness in the ball influences the result to an unknown and perhaps variable extent.

#### ATTEMPTS TO MAKE HARDER BRINELL BALLS.

The Brinell balls available at present are generally made of a high carbon steel (carbon about 1.20 per cent.) sometimes containing chromium, usually not over 1 per cent. They are hardened in water, and not tempered, or tempered at low temperature. They represent the maximum hardness that is generally obtained in hardened steel objects—about 700 Brinell.

In order to eliminate, or minimise, the error in the Brinell test on hardened steel due to flattening of the ball, efforts have been made to produce a harder ball. For some years an American steel ball manufacturing firm has supplied special Brinell balls of greater hardness. They are made of a chromium-tungsten steel (carbon = 1.40, chromium = 0.60, tungsten = 4.0 per cent.). These balls, as will be seen later, are somewhat harder

than ordinary balls but not enough to enable accurate hardness determinations to be made on hardened steel.

The author has also made attempts to produce balls of increased hardness by the use of alloy steels.<sup>1</sup> Ten-millimetre balls were made of steels of the following composition :

- (1) C = 0.62, W = 5.6 per cent. (magnet steel).
- (2) C = 0.90, Cr = 1.0, Si = 1.6 per cent.

These experiments were not successful. The magnet steel balls could not be hardened to fully martensitic structure even by quenching in water. This is a peculiar phenomenon that sometimes occurs in hardening tungsten steels. The chromium-silicon steel balls were only slightly harder than the ordinary balls made of carbon steel.

Somewhat better results were obtained by special heat treatment, using a steel having the composition : carbon = 1.10, chromium = 0.60 per cent. The soft balls were first heated to 900° C. and cooled in boiling water, thus producing a homogeneous sorbitic structure. They were then hardened from 760° C. in water and left untempered. The structure resulting consisted of extremely fine martensite with the hypereutectoid cementite distributed in numerous small grains of about 0.0001 millimetres size. The hardness of the finished balls was distinctly greater than that of ordinary Brinell balls, and very uniform. This increase in resistance to permanent deformation is assumed to be due to the great number of small cementite particles, in combination, perhaps, with the fineness of the martensitic matrix, the latter being a secondary result of the former. The case is an example of "slip interference." The improvement obtained, which will be illustrated by test results given later, was not such, however, as to eliminate the error due to flattening of the ball in the Brinell test on hardened steel.

#### HARDENING HARDENED STEEL BALLS BY COLD-WORKING.

Although cold-working is extensively used as a means of increasing hardness and strength of metals, it has, to the author's knowledge, not been applied to fully hardened steel, that is steel having martensitic structure. The reasons for this are obvious.

<sup>1</sup> These and the following experiments were made in the works and laboratory of A. B. Svenska Kullagerfabriken (S.K.F.) in Gothenburg.

The brittleness of a hardened steel object does not permit much permanent deformation without cracking, particularly where discontinuities in shape would act as notches in promoting such cracking. An attempt to deform a file permanently by bending may be given as an extreme example of this. Furthermore, the large forces required permanently to deform hardened steel seem to stand in the way of such treatment. On the other hand, a polished high-grade steel ball represents such a combination of suitable properties that it appeared to be possible to cold-work its surface without danger of cracking. Its simplicity of form and freedom from surface imperfections cannot be surpassed. Also, such balls can be, and generally are, heat-treated, that is annealed and hardened, with sufficient care to ensure the maximum amount of toughness that can be associated with a high degree of hardness. As will be seen from the following, a considerable hardening effect was produced in the surface layer of the balls by the cold-working treatment.

The balls subjected to cold-working were ordinary Brinell balls made by A. B. Svenska Kullagerfabriken in Gothenburg, and had the following composition: carbon, 1.20 per cent., chromium, nil. After several preliminary experiments the following procedure was adopted. The balls, which were finely polished, formed part of a ball-bearing of the so-called radial type, having somewhat thicker race-rings than usually employed. The balls were separated from each other by a cage that enclosed them only at one side of the bearing, leaving the balls free to be touched at the other side. The bearing was mounted on a horizontal shaft, the outer ring being well fitted in a cylindrical housing provided with means of applying the necessary load. The experimental arrangement is illustrated by Fig. 1. The load is hung on the shank of the housing by means of lever and weights. A flexible contact finger is attached to the housing as shown. This finger touches the balls successively every time they pass the unloaded part of their rolling path. This repeatedly changes the rolling axis of each ball. Before this device was applied, it happened that the "pole" regions of the balls did not become cold-worked. For quantity production a somewhat different machine was designed on the same principle. In this machine four sets of balls were treated at the same time.



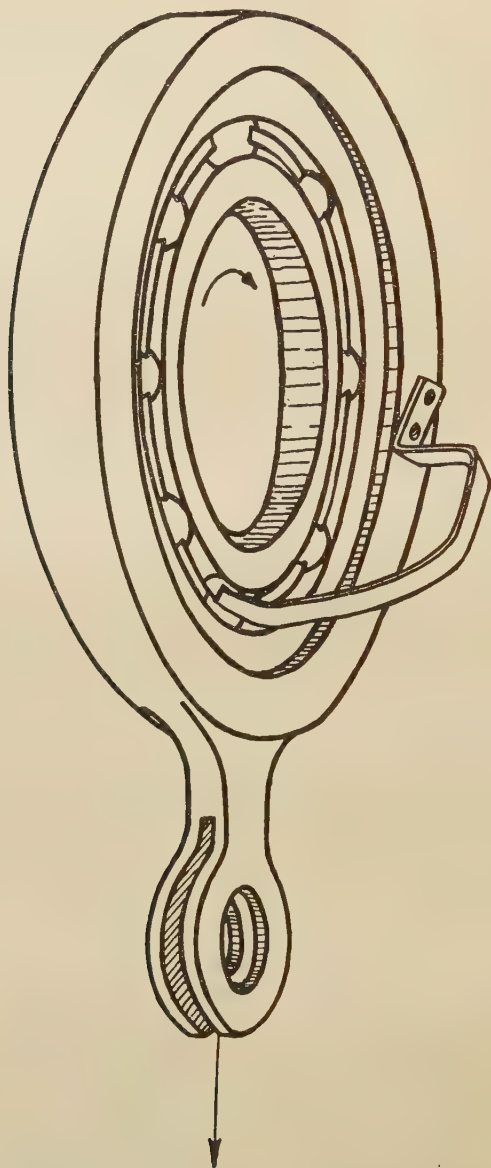


FIG. 1.—Apparatus for Cold-Working of 10-millimetre Balls.

The following data apply to treatment of 10-millimetre balls :

Shaft diameter	= 60 millimetres.	
Outside diameter of bearing	= 110	"
Number of balls in each bearing	= 8	
Speed of shaft	= 1440 r.p.m.	
Speed of balls	= 635 r.p.m., equivalent to 2.82 m/sec.	
Load on bearing	= 3500 kilogrammes.	
Maximum load on each ball	= 2200	" <sup>1</sup>
Time of treatment		= 3 minutes.
Number of applications of maximum load on each ball during period of treatment		= 1905.

The bearing is lubricated with a continuous stream of mineral oil.

The load applied on each ball is about twenty-two times greater than the load sustained by each ball in the ordinary service of a ball-bearing of this size, and about one-third of the breaking load obtained when two 10-millimetre balls are pressed against each other in a crushing test. Obviously the balls would not endure such drastic treatment as described for any extended period. They would "flake" or crack if the treatment were continued for hours; the rings fail sooner or later by flaking, and have to be renewed. In spite of the steady supply of lubricant the temperature of the bearing continues to rise during the rotation. After two or three runs the shaft is therefore cooled by water. The higher the load the harder becomes the ball, and the deeper will be the penetration of the cold-working effect. This is shown in Table I., where results of a series of Brinell tests on a piece of hardened magnet steel are given. The balls were 10 millimetres, and had been treated with different loads in the cold-working process. The bearing was run at 2000 r.p.m. for two minutes in each case. The load of the Brinell test was 3000 kilogrammes. Hardness numbers, and the permanent flattening of the ball in the test,  $\delta$ , measured by a so-called mini-meter according to Hirth, are given. The balls were etched, as described later, in order to facilitate accurate measurement of the impression.

3500 kilogrammes was chosen as standard load in cold-working, being the maximum that may be applied without risk of premature failure of balls or races.

<sup>1</sup> Compare Stribeck: "Kugellager für beliebige Belastungen," *Zeitschrift des Vereines Deutscher Ingenieure*, 1901, p. 73.

TABLE I.—*Brinell Tests 10 mm. 3000 kg. on Hardened Magnet Steel.*

Load in Cold-Working. Kg.	Hardness Number. H.	Permanent Flattening of Ball, $\delta$ . Mm.
0	667	0.038
1000	686	0.030
1500	679	0.027
2000	700	0.026
3000	706	0.015
4000	716	0.013

In order to ensure uniform treatment for all balls and all over the surface of each ball, the variation in diameter in a set of balls or in each ball is controlled to within 0.001 millimetre. This presents no manufacturing difficulties in modern ball production. The variation in diameter after cold-working has been repeatedly measured and was never found to exceed 0.0005 millimetre.

Five-millimetre balls were also cold-worked in the manner described. In this case the bearing contained twelve balls, and the load was 1300 kilogrammes.

#### THE STRUCTURE OF COLD-WORKED HARDENED STEEL.

It has not been possible to detect any difference in the micro-structure of a ball before and after cold-working, or between the cold-worked surface portion and the unaffected interior of the ball.

Several macro-etching solutions were also tried. In applying the well-known reagent of Stead on a section through the centre of a cold-worked ball, a band appeared along the circumference that showed a faint contrast against the central portion. Somewhat more distinct was the effect of Fry's<sup>1</sup> method, modified by dipping for five seconds and rubbing with cupric chloride for fifteen seconds only. The band was lighter than the centre. Other macro-etching reagents, including those of Heyn, Rosenhain and Haughton, Le Chatelier, Oberhoffer, and also common dilute acid solutions, were tried but failed to produce such contrast.

<sup>1</sup> *Kruppsche Monatshefte*, 1921, p. 117.

By the use of Stead's and Fry's reagents the approximate depth of penetration of the cold-working effect was ascertained to be as follows :

0.75	millimetre	for	10-millimetre	balls.
0.40	„	„	5-	„

Several tests were made in order to estimate or measure the hardness and strength of cold-worked hardened steel balls :

- (1) Martens scratch test.
- (2) Herbert pendulum hardness test.
- (3) Rockwell hardness test using a diamond cone.
- (4) Deformation test ball against ball, the permanent flattening for a certain load being measured.
- (5) Comparative Brinell tests using ordinary, special, and cold-worked Brinell balls on a series of steel specimens of different hardness, including the hardest steel procurable. In this series the effect of flattening of the ball upon the Brinell hardness number was studied.
- (6) Rebound test.
- (7) Crushing test.

#### MARTENS SCRATCH TEST.

Polished sections of cold-worked balls were scratched with a conical diamond point of  $100^\circ$  angle, using loads up to 50 grammes. The width of the scratch was found to be constant throughout the section, indicating that the resistance against deformation by scratching was not altered by cold-working.

#### HERBERT PENDULUM HARDNESS TEST.

Through the courtesy of Messrs. Bergman & Beving, Stockholm, a Herbert pendulum hardness tester was kindly put at the author's disposal. Only so-called time tests were made.

In using a 1-millimetre steel ball as pivot for the pendulum, very irregular results were obtained as soon as cold-worked balls were tested. Upon examination of the pivot ball by the microscope the ball was found to be flattened.

Consequently the steel ball was replaced by a 1-millimetre ruby ball. The pendulum was set to give ten swings in one hundred seconds on a standard glass plate. In doing this it

was found difficult to obtain constant results, presumably on account of minute cracks forming at the glass surface in contact with the ball. The results given in Table II. are therefore to be considered as comparative only.

TABLE II.—*Herbert Pendulum Hardness Tests.*

Object.	Surface Tested.	Time of Ten Swings. Seconds.		Average.
Ordinary 10-millimetre ball.	4 millimetres ground, flat.	86·7	88·1	87·3
		86·2	88·2	...
Cold-worked 10-millimetre ball.	4 millimetres ground, flat.	95·4	93·7	94·5

The results indicate a considerable increase of hardness by cold-working.

#### ROCKWELL DIAMOND CONE HARDNESS TEST.

A diamond cone of  $120^\circ$  angle with the point slightly rounded is pressed into the surface of the specimen. The permanent depth of impression produced by increasing the load from 10 kilogrammes to 150 kilogrammes is recorded, and serves as a basis for the hardness number, which is read directly on a dial. The instrument is convenient and rapid in operation.

The Rockwell hardness numbers obtained, all referring to the so-called C scale (using diamond cone), are given in Table III.

From these figures it may be concluded that any increase in hardness due to cold-working of hardened balls is not with certainty detected by the Rockwell diamond cone test.

#### DEFORMATION TEST BALL AGAINST BALL.

When two balls of the same size and hardness are pressed against each other under sufficient load, two flats of the same size are formed, which, after unloading, assume a slightly convex shape. The size of the permanent "flats" and the reduction of diameter at the loaded points are functions of the hardness.



If one of the balls is harder than the other, the former will receive no permanent impression, or a slight one, whereas the impression on the latter is apt to be plane or concave. Thus the

TABLE III.—*Rockwell Hardness Tests on 10- and 5-Millimetre Balls (Diamond Cone).*

Object.	Surface Tested.	Hardness Number.		Average.
Ordinary 10-millimetre ball.	Spherical surface.	68·2 68·0	67·4	67·9
Ordinary 10-millimetre ball.	3 millimetres ground, flat.	69·4 69·5	69·1	69·3
Ordinary 5-millimetre ball.	Spherical surface.	65·4 64·4	64·6 64·4	64·7
Ordinary 5-millimetre ball.	1·5 millimetre ground, flat.	67·8 69·0	66·3	67·7
Cold-worked 10-millimetre ball.	Spherical surface.	67·6 68·0 68·3	68·0 68·6	68·1
Cold-worked 10-millimetre ball.	3 millimetres ground, flat.	68·8 68·4	69·5	68·9
Cold-worked 5-millimetre ball.	Spherical surface.	66·5 66·4 64·8	66·9 65·1	65·9
Cold-worked 5-millimetre ball.	1·5 millimetre ground, flat.	67·1 66·0	68·9	67·3

relation in hardness between two balls may be judged, somewhat exaggeratedly, from the permanent reduction of their diameters.

Several grades of balls were tested against a cold-worked ball in each case :

SKF ordinary Brinell ball, not tempered, cold-worked, called SKF cold-w.

SKF ordinary Brinell ball, not tempered, called SKF ord.

SKF ball, tempered to 225° C., called SKF 225°.

SKF ball, heat-treated as described, to give fine-grained structure, called SKF fine-gr.

Special Brinell ball of American make (CrW steel), called CrW.

The load, 1000 kilogrammes, was applied in a Brinell press using a known fixture for centring the balls, shown in Fig. 2.

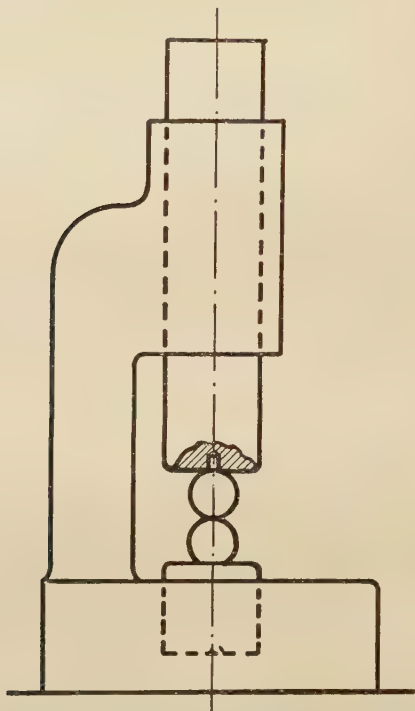


FIG. 2.—Fixture for Deformation Tests Ball against Ball.

The reduction of diameter,  $\delta$ , as measured by a minimeter, is given in Table IV.

The relative hardness of each grade of balls is plainly seen from the figures in the table.

#### COMPARATIVE BRINELL TESTS

The objects of these tests were two :

1. To ascertain if, or to what extent, in testing hardened steels, the error in the Brinell number arising from the flattening of the ball could be eliminated, or minimised, by the use of the cold-worked ball ; and
2. To study the relationship between this error and the amount

of flattening of the ball on one hand, and the hardness or grade of ball as well as the hardness of the test specimen on the other hand.

A Brinell press of common type, from the Aktiebolaget Alpha, was used. The balls were 10 millimetres, etched, as later described,

TABLE IV.—*Deformation Test Ball against Ball 10 mm. 1000 kg.*

Test No.	$\delta$ mm.					
	SKF cold-w.		SKF ord.	SKF 225°.	SKF fine-gr.	CrW.
1	0·0135	0·0135	...	...	...	...
2	0·0135	0·013	...	...	...	...
3	0·007	...	0·032	...	...	...
4	0·007	...	0·030	...	...	...
5	0·005	...	...	0·038	...	...
6	0·004	...	...	0·038	...	...
7	0·0065	...	...	...	0·026	...
8	0·0075	...	...	...	0·026	...
9	0·007	...	...	...	...	0·026

to give easily measurable impressions. The load, 3000 kilogrammes, was held for ten seconds. The test specimens were polished; the surfaces were all etched before final polishing in order to ensure that no soft spots from hardening or grinding were present. The diameter of impression was measured with a Reichert Brinell microscope magnifying thirty diameters. The accuracy of measurement is estimated to  $\pm 0\cdot006$  millimetre corresponding to  $\pm 4$  units in the hardness number, when this is 700. The flattening of the ball was measured as decrease of diameter with a minimeter to  $\pm 0\cdot0005$  millimetre.

The following grades of balls were used, denominated as above:

SKF cold-w.; SKF ord.; SKF 225°; SKF fine-gr.; CrW.

The following materials were used as test specimens:

- Test specimen I.: Hardened chromium steel, tempered at 410° C., hardness number 506.  
 „ „ II.: Hardened chromium steel, tempered at 350° C., hardness number 562.  
 „ „ III.: Hardened chromium steel, tempered at 260° C., hardness number 635.  
 „ „ IV.: Hardened chromium steel, tempered at 150° C., hardness number 695 (corrected).  
 „ „ V.: Hardened high-speed steel, hardness number 735 (corrected).

TABLE V.—*Comparative Brinell Tests 10 mm. 3000 kg.*

Balls Used.	Test Specimen I.			Test Specimen II.			Test Specimen III.			Test Specimen IV.			Test Specimen V.		
	$H_c = 506.$			$H_c = 562.$			$H_c = 635.$			$H_c = 695.$			$H_c = 735.$		
	$d.$	H.	$\delta.$	$d.$	H.	$\delta.$	$d.$	H.	$\delta.$	$d.$	H.	$\delta.$	$d.$	H.	$\delta.$
SKF tempered 225°	2.732	502	0.0105	2.605	553	0.017	2.490	606	0.030	2.440	632	0.043	2.410	648	0.046
	2.732	502	0.0115	2.613	550	0.0195	2.504	599	0.034	2.444	630	0.0475	2.408	649	0.053
	2.735	501	0.0105	2.605	553	0.0165	2.490	606	0.028	2.448	628	0.039	2.413	646	0.051
	2.724	505	0.0115	2.605	553	0.0195	2.492	605	0.031	2.447	628	0.044	2.415	645	0.053
	2.737	500	0.0115	2.600	555	0.0195	2.500	601	0.033	2.441	631	0.045	2.412	647	0.0555
Average	...	502	0.0111	...	553	0.0184	...	603	0.0310	...	630	0.0437	...	647	0.0517
$H_c-H$	4			9			32			65			88		
SKF ordinary	(2.747)	(496)	(0.011)	2.612	550	0.017	(2.480)	(611)	(0.0205)	2.392	658	0.029	2.368	672	0.037
	2.725	505	0.012	2.610	551	0.016	2.460	621	0.021	2.390	659	0.028	2.365	673	0.041
	2.735	501	0.0085	2.615	549	0.015	2.470	616	0.020	2.375	667	0.026	2.374	668	0.036
	2.737	500	0.0105	2.610	551	0.016	2.471	616	0.022	2.375	667	0.028	2.375	667	0.041
	2.725	505	0.0085	2.600	555	0.0155	2.470	616	0.0215	2.390	659	0.027	2.346	684	0.0355
Average	2.724	505	0.010	2.602	554	0.0165	2.467	618	0.0245	2.387	661	0.030	...	...	...
	2.728	504	0.0125	2.602	554	0.017	2.471	616	0.0255	2.387	661	0.0325	...	...	...
$H_c-H$	...	503	0.0103	...	552	0.0162	...	617	0.0224	...	662	0.0286	...	673	0.0381
	3			10			18			33			62		

CrW.	2.725	505	...	2.598	556	0.016	2.470	616	0.0235	2.402	652	0.029	2.377	666	0.0305
	2.722	506	...	2.600	555	0.018	2.471	616	0.0255	2.380	665	0.031	2.372	669	0.034
	2.725	505	0.007	2.595	558	0.010	2.445	629	0.016	2.353	680	0.0215	2.347	684	0.0225
	2.722	506	0.009	2.597	557	0.012	2.444	630	0.018	2.350	682	0.0235	2.348	683	0.026
	2.724	505	0.0065	2.597	557	0.0095	2.458	623	0.017	2.362	675	0.024	2.346	684	0.026
Average	...	505	0.0075	...	557	0.0131	...	623	0.0200	...	671	0.0258	...	677	0.0278
H <sub>c</sub> -H	1			5			12			24			58		
SKF fine- grained	2.720	507	0.0055	2.595	558	0.010	2.453	625	0.0175	2.373	669	0.0235	2.342	687	0.027
	2.722	506	0.006	2.597	557	0.011	2.455	624	0.0185	2.372	669	0.029	2.343	686	0.0305
	2.720	507	0.0055	2.595	558	0.0095	2.460	621	0.0175	2.380	665	0.025	2.347	684	0.027
	2.722	506	0.006	2.597	557	0.011	2.467	618	0.0185	2.375	667	0.0285	2.348	683	0.0295
	2.722	506	0.0085	2.597	557	0.0125	2.450	627	0.0185	2.368	672	0.026	2.325	697	0.033
Average	...	506	0.0063	...	557	0.0098	...	623	0.0181	...	668	0.0268	...	687	0.0294
H <sub>c</sub> -H	0			5			12			27			48		
SKF cold- worked	2.742	(498)	0.002	2.590	560	0.0035	2.433	636	0.006	2.345	685	0.0105	2.292	717	0.014
	2.720	507	0.003	2.585	562	0.005	2.423	641	0.007	2.338	689	0.0105	2.284	723	0.0135
	2.720	507	0.001	2.585	562	0.004	2.440	632	0.0045	2.345	685	0.011	2.312	705	0.010
	2.722	506	0.001	2.595	558	0.005	2.438	633	0.006	2.345	685	0.0115	2.315	703	0.011
	2.718	507	0.0005	2.582	563	0.0045	2.440	632	0.0055	2.345	685	0.0125	2.312	705	0.015
Average	2.722	506	0.0005	2.582	563	0.0045	2.436	634	0.006	2.345	685	0.0115	2.300	712	0.016
	2.722	506	0.0015	2.582	563	0.003	2.438	633	0.007	2.345	685	0.011	...	...	...
	...	506	0.0013	...	562	0.0042	...	634	0.0060	...	686	0.0112	...	711	0.0132
	0			0			1			9			24		
	0			0			1			9			24		
H <sub>c</sub> -H	0			0			1			9			24		



The test specimens I., II., III., and IV. were taken from the same ring of a ball-bearing of chromium steel, having the following composition: carbon 1.0, chromium 1.5 per cent. The

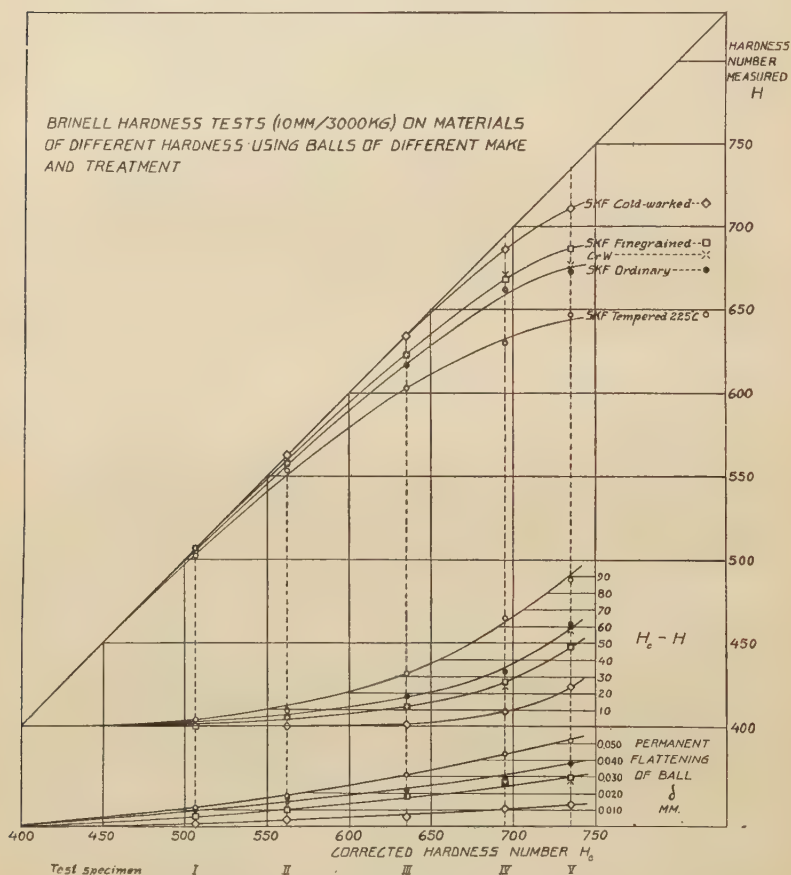


FIG. 3.—Comparative Brinell Hardness Tests.

side surface, 22 millimetres wide, was used for the tests. The high-speed steel specimen, kindly supplied by Messrs. Hadfield, Ltd., Sheffield, as representing a Brinell hardness of 710 to 720, had the following composition: carbon 0.75, chromium 4.2, tungsten 15.5 per cent., vanadium nil. The tested surface was 40 by 25 millimetres.

All impressions were made with separate balls, except those made with the CrW balls. Of these only five balls were available, which had to be used in different positions.

The results are given in Table V. (pp. 194, 195), and the average plotted in the diagram in Fig. 3.

The following symbols are used :

$d$  = diameter of impression in millimetres.

$H$  = the apparent hardness number as calculated upon  $d$ .

$H_c$  = a corrected hardness number obtained by estimating the error produced by the measured amount of ball flattening.

$\delta$  = permanent flattening of ball in millimetres.

If in testing the same material with balls of different hardness the hardest ball receives no permanent flattening, obviously the  $H$  value obtained with this ball will just be the correct hardness number  $H_c$  for the material in question.

The error in  $H$  for any given softer ball is thus found, and may then be correlated to  $\delta$  for the same ball. It should be stated here that the elastic deformation of the ball under load is not considered in arriving at  $H_c$ .

The softest material tested, test specimen I., with  $H_c = 506$ , was hard enough to cause a flattening averaging 0.0013 millimetre on the hardest ball (SKF cold-w.), and a flattening of 0.0063 millimetre on the next hardest ball (SKF fine-gr.). Still the  $H$  value obtained with these two kinds of ball was practically the same. It is therefore assumed that the error in  $H$  for these two balls is nil in this case. Proceeding to harder materials,  $\delta$  and  $H_c - H$  are gradually increasing. In order to arrive at  $H_c$  the following corrections in hardness number obtained with SKF cold-worked ball have been added to the  $H$  value.

Test specimen II.:	$H = 562$ ;	$\delta = 0.0042$ ;	$H_c - H = 0$ ;	$H_c = 562$ .
„ „ III.:	$H = 634$ ;	$\delta = 0.0060$ ;	$H_c - H = 1$ ;	$H_c = 635$ .
„ „ IV.:	$H = 686$ ;	$\delta = 0.0112$ ;	$H_c - H = 9$ ;	$H_c = 695$ .
„ „ V.:	$H = 711$ ;	$\delta = 0.0132$ ;	$H_c - H = 24$ ;	$H_c = 735$ .

Obviously these corrections are somewhat arbitrary, particularly for the two hardest materials, IV. and V.; but some guidance is obtained from the results on test specimens I. and II., at the same time bearing in mind that a certain  $\delta$  will be correlated with greater correction in  $H$  the higher the latter is.

Certain discrepancies in  $\delta$  and  $H_c - H$  are seen in the table and in the diagram of Fig. 3. They are, however, not greater

than could be expected, considering the sources of error inevitable in this test, such as variation of hardness in balls of the same kind, and similar variations within the same specimen. The CrW balls were not uniformly hard, as is seen from the individual tests.

The main conclusions to be drawn from the Brinell tests given are summarised in Table VI., showing values of  $\delta$  and  $H_c - H$  selected from the curves in Fig. 3 for the five ball grades tested, and for representative materials having hardness numbers 500, 600, 700, and 735 respectively.

TABLE VI.

	$H_c$ .	Ball Grade.				
		SKF 225°.	SKF ord.	CrW.	SKF fine-gr.	SKF cold-w.
Permanent deformation of ball $\delta$ millimetres.	500	0.011	0.009	0.005	0.005	0.001
	600	0.026	0.019	0.014	0.014	0.005
	700	0.045	0.032	0.025	0.025	0.011
	735	0.052	0.038	0.028	0.029	0.013
Correction in hardness number $H_c - H$ .	500	4	3	1	0	0
	600	21	14	8	8	0
	700	65	38	29	29	9
	735	88	62	58	48	24

From the view-point of practical importance the following statements may be made. Hardness numbers that are correct within 1 per cent., as far as the effect of ball flattening is concerned, may be obtained by using :

SKF 225°	balls on materials of hardness number less than 500 to 525
SKF ord.	" " " " " 525 " 550
CrW	" " " " " 575 " 600
SKF fine-gr.	" " " " " 575 " 600
SKF cold-w.	" " " " " 675 " 700

#### COLD-WORKING SPECIAL BALLS.

It was considered of interest to try cold-working on balls which were, for reasons of composition or heat treatment, harder than the ordinary grade of Brinell balls. The special CrW steel balls of American origin, CrSi steel balls mentioned above, and

the SKF fine-grained balls were subjected to cold-working, and afterwards used for Brinell tests on the Hadfield high-speed steel specimen. The results obtained agreed very well with those found in using the ordinary cold-worked balls. It seems, therefore, that the superiority in hardness of certain balls of special composition or heat treatment over ordinary steel balls disappears when the various grades of balls are cold-worked, or, in other words, there appears to be a limit to the hardness value obtainable by cold-working hardened steel irrespective of composition and previous heat treatment. This conclusion is confirmed by the rebound tests described later.

### TEMPERING AFTER COLD-WORKING.

It might be expected that tempering to some moderate temperature after cold-working would be beneficial in increasing the hardness still further. In Table VII. are collected some data obtained in Brinell testing a piece of hardened magnet steel with cold-worked balls that had been tempered at different temperatures after cold-working.

TABLE VII.—*Brinell Tests 10 mm. 3000 kg. with SKF Cold-Worked Balls, Tempered at Different Temperatures after Cold-Working.*

Tempering Temperature, °C.	δ Millimetres.	H.
Not tempered	0·015	706
150	0·014	692
175	0·020	687
200	0·022	684
225	0·033	668
250	0·050	633

The conclusion is that the hardness of cold-worked balls is not raised by tempering to 150° C. Tempering at higher temperature gradually lowers the hardness.

### REBOUND TESTS.

The test arrangement is shown in Fig. 4. The balls were allowed to roll without initial speed along the incline A to B

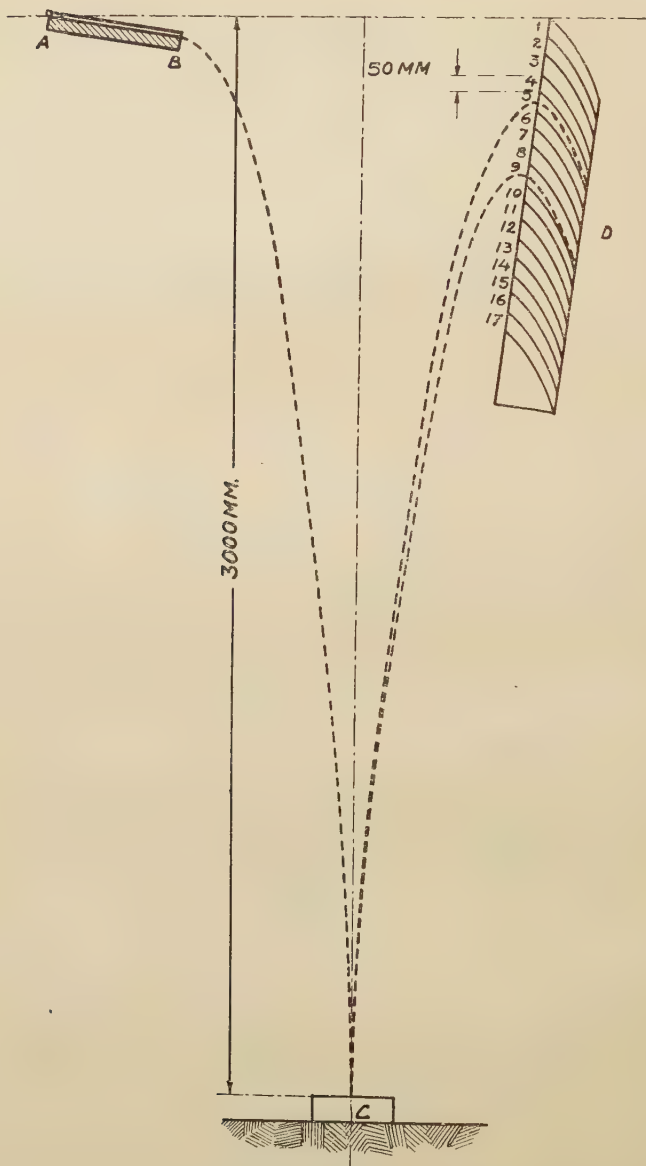


FIG. 4.—Apparatus for Rebound Tests on Balls.



of V-section. After leaving A-B they dropped on to the horizontal upper surface of the hardened chromium steel anvil C, placed 3 metres below A. After rebounding, the balls were caught at the apex of the parabola in a receiver, divided into pockets of 50-millimetre openings, separated by 1-millimetre sheet plate. The pockets were numbered as shown in the figure. It is essential that the apparatus be clean, the anvil hard, and its surface accurately plane.

Balls tested were 10 millimetres. For each lot of balls the test was repeated one to four times. The number of balls collected in each pocket was counted every time, and the average pocket number for each grade of balls was calculated and called the rebound index. The harder the ball the lower is this index. It was found that a certain dispersion occurred within each grade of balls. It never exceeded, however, the range represented by two adjacent pockets—*i.e.* 100 millimetres. The rebound indices obtained are given in Table VIII., arranged according to increasing hardness.

When the number of balls in the lot exceeded about fifty, the index at repeated tests was found consistent within  $\pm 0.2$  unit.

The hardness relation between balls of different make and treatment found in previous tests is confirmed by the results of the rebound tests, and some additional results are obtained. As a summary the following may be stated.

Tempering of ordinary balls at  $150^{\circ}\text{C}$ . does not lower the rebound hardness, but perhaps slightly raises it, whereas tempering at  $225^{\circ}\text{C}$ . lowers the hardness to a marked extent.

Balls tested of CrSi and CrW steel were somewhat harder than carbon steel balls. Balls specially heat-treated to produce fine-grained structure were found to belong to the same hardness class as the alloy steel balls.

Cold-working raises the rebound hardness of the balls considerably: for ordinary balls from index 8.8 to 5.4, for CrSi steel balls from 8.3 to 5.3, for fine-grained balls from 8.0 to 5.2. Thus the composition, or previous heat treatment of the balls, provided they are hardened, has little or no influence upon the ultimate hardness after cold-working.

Storing of cold-worked balls for an hour, a week, or a month caused no change in rebound hardness.

TABLE VIII.—*Rebound Tests on 10-Millimetre Balls. Height of Fall, 3 Metres.*

Make and Treatment of Balls.	Number of Rebounds.	Rebound Index.
SKF balls tempered 225° . . . . .	154	9·7
SKF Brinell balls, ordinary, not tempered . . .	249	8·8
Brinell balls of British make . . . . .	90	8·8
SKF Brinell balls, tempered 150° . . . . .	87	8·5
CrSi steel balls, not tempered . . . . .	90	8·3
CrW steel balls, American make . . . . .	3	8·0
SKF fine-grained balls, not tempered . . . . .	90	8·0
CrW steel balls, cold-worked . . . . .	3	6·0
SKF ordinary Brinell balls, cold-worked, tempered 150°	90	6·0
SKF ordinary Brinell balls, cold-worked, tempered 100°	122	5·7
SKF ordinary Brinell balls, cold-worked, not tempered	1429	5·4
Brinell balls of British make, cold-worked . . .	12	5·3
CrSi steel balls, cold-worked . . . . .	21	5·3
SKF fine-grained balls, cold-worked . . . . .	76	5·2

Tempering of cold-worked balls at 100° C. was of no influence on, tempering at 150° C. distinctly lowered the hardness of cold-worked balls.

#### CRUSHING TESTS ON ORDINARY AND COLD-WORKED BALLS.

Steel balls are sometimes tested to destruction by compression, placing three balls on the top of one another in a fixture like that shown in Fig. 2, the load being gradually increased until the balls suddenly break, usually all at the same moment. Of course the fracture is preceded by a considerable amount of flattening. Ordinary 10-millimetre balls, untempered, and such balls tempered to 150° C., were cold-worked and crushing tests were made

on the balls in the four conditions. The results are given in Table IX.

TABLE IX.—*Crushing Tests, 10-Millimetre Balls.*

Treatment of Balls.	Crushing Strength. Tons.				Average. Tons.
Not tempered, not cold-worked .	4.9	5.8	6.3	...	5.7
Not tempered, cold-worked .	8.1	7.9	7.3	6.8	7.5
Tempered 150°, not cold-worked .	6.3	7.1	5.9	6.5	6.5
Tempered 150°, cold-worked .	6.8	6.9	7.6	7.4	7.2

As is to be expected, the concordance between individual values is not very good ; still the averages show that cold-working raises the crushing strength of hardened balls somewhat and to a rather definite value irrespective of whether the balls were tempered to 150° C. or not. Tempering to 150° C. alone also raises the crushing strength somewhat, probably due to relief of hardening stresses.

The fact that the increased hardness of the cold-worked balls manifests itself in the Brinell test, in the deformation test ball against ball, and in the rebound test, but not in the Martens scratch test, and not, or only slightly, in the Rockwell diamond cone test, deserves attention. In all cases the resistance against permanent deformation is involved but the manner of deformation is different, especially the shape of the surface that causes deformation.

The indenting cone of the Rockwell test will cause higher secondary tensile stresses at right angles to the direction of the pressure than the plane surface of the anvil in contact with the ball in the rebound test, and still higher than the already deformed surface of a Brinell specimen. It might be that cold-working, at least of the kind under discussion, raises the resistance to such deformation only as is brought about by pressure combined with not too high secondary tension.

#### ACCURACY OF MEASUREMENT IN BRINELL TESTS ON HARDENED STEEL. USE OF ETCHED BALL.

Everybody who has made Brinell tests on hardened steel will probably concur in the statement that the accurate determination

of the diameter of impression is rather difficult. This is due to the small size and shallowness of the impression, and the consequent lack of contrast between the impression surface and the surrounding surface.

In order to obtain sharper definition of the impression circle the author has tried with success to use etched balls for the test.<sup>1</sup> By this means the surface of the impression presents a dull lustre when viewed by the eye or in the microscope. The outline of the impression thus becomes sharply defined, and can be easily and accurately read in the microscope. The etching of the ball, after careful cleaning in alcohol, is done in 1 per cent. solution of nitric acid in alcohol, the balls being continuously moved in the solution for about three minutes. They are then washed in alcohol and wiped without rubbing against each other. This would partly destroy the dullness of the surface.

The effect of using an etched ball is seen by comparing Figs. 5, 6, and 7 (Plate X.), showing at a magnification of 20 diameters Brinell impressions made with a 10-millimetre ball and 3000 kilogrammes load on a piece of hardened chromium steel ( $H = 653$ ) finished on Hubert 1 emery-paper. Figs. 5 and 6 represent the same impression made with a bright ball; Fig. 7 another impression made with an etched ball. In taking Fig. 5 the light fell obliquely on to the specimen; in Fig. 6 it was at the same time reflected by a paper slip placed at the other side of the impression. In Fig. 5 the diameter is impossible to measure; in Fig. 6 it is possible to read the diameter sharply along the scratches but not across them. In Fig. 7 the dull impression from the etched ball is sharply outlined throughout its circumference. The light fell at a steep angle on to the surface in the direction of the scratches. In Fig. 8 (Plate X.) an impression is shown made with a 10-millimetre etched ball on the polished sample of Hadfield high-speed steel mentioned above. Attention is called to the small circle in the centre of the impression. This is explained later.

In examining at high magnification the dull impression from an etched ball on a polished sample it is found that the dullness is due to numerous small impressions from the free cementite

<sup>1</sup> A brief account of this method was submitted to The Committee for New Hardness Testing Machine of the National Research Council of U.S.A. in May 1920.



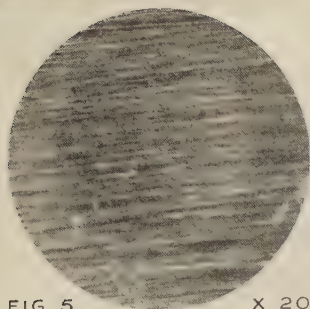


FIG. 5

X 20

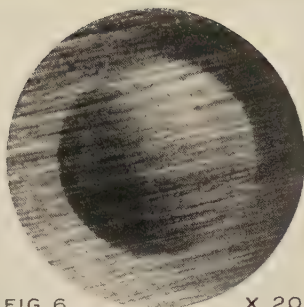


FIG. 6

X 20

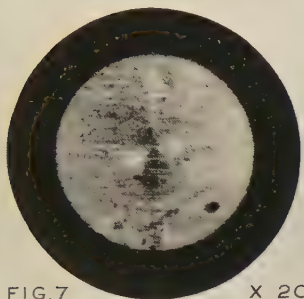


FIG. 7

X 20

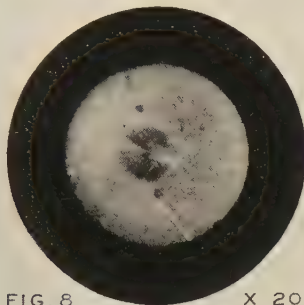


FIG. 8

X 20

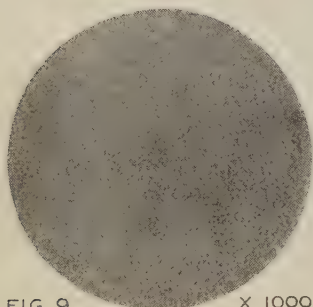


FIG. 9

X 1000

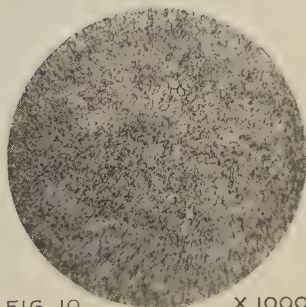


FIG. 10

X 1000

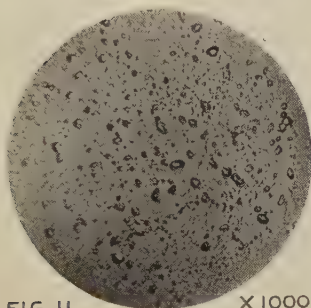


FIG. 11

X 1000

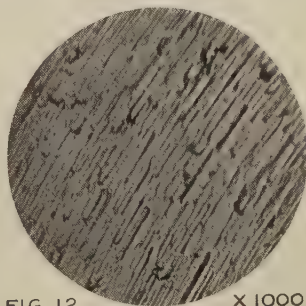


FIG. 12

X 1000

FIG. 5.—Brinell impression ( $\times 20$ ) on hardened chromium steel, using bright ball.

FIG. 7.—Brinell impression ( $\times 20$ ) on hardened chromium steel, using etched ball.

FIG. 9.—Brinell ball, etched section ( $\times 1000$ ).

FIG. 11.—Brinell impression, using etched ball, outer portion ( $\times 1000$ ).

FIG. 6.—Brinell impression ( $\times 20$ ) on hardened chromium steel, using bright ball, better illumination.

FIG. 8.—Brinell impression ( $\times 20$ ) on hardened high-speed steel, using etched ball.

FIG. 10.—Brinell ball, etched surface ( $\times 1000$ ).

FIG. 12.—Brinell impression, using etched ball, central portion ( $\times 1000$ ).

(All reproduced approximately half original size.)

[To face p. 204.]





particles standing out in relief on the ball surface after etching.<sup>1</sup> This is illustrated by Fig. 9, showing the microstructure of the ball (carbon = 1·20 per cent.) as seen on a lightly etched section, further Fig. 10 (Plate X.) showing the ball surface rather deeply etched for the Brinell test, and Fig. 11 taken from the outer portion of a Brinell impression made on a steel surface, using the etched ball seen in Fig. 10, all magnified 1000 diameters. Fig. 12 illustrates the central circular part of the impression. Instead of small holes as in Fig. 11, concentric scratches are visible. These are formed as a result of a slight turning movement of the ball together with its holder and the piston in the beginning when the load is being applied. This rotary movement is caused by the small torque from the helical spring acting on the piston of the press and having the function to bring this back to a zero vertical position. The rotary movement stops when the area of contact between the ball and the specimen reaches a certain magnitude, sufficient to supply the friction torque required to resist the torque mentioned.

By etching the ball in the manner described its diameter is diminished by 0·001 to 0·002 millimetre. This small decrease in size of ball does not affect the result of the test.

In connection with the method described to facilitate the accurate measurement of Brinell impressions on hardened steel a few words may be said about the sensitiveness of the measuring instrument. The type of microscope commonly used for this purpose magnifies 10 diameters, and has an eye-piece micrometer graduated in tenths of a millimetre. This allows an accuracy in determining the diameter of impression of about  $\pm 0\cdot02$  millimetre, which is equivalent to  $\pm 12$  units in the hardness number when testing a steel of 700 Brinell with 10-millimetre ball; when using 5-millimetre ball the possible error is extended to  $\pm 24$  units.

When etched balls are used for the Brinell test the contour of the impression is so sharply defined that the diameter can be measured with greater precision. The microscope used for the tests described above, of Reichert's make, gave a magnification of 30 diameters, and had an eye-piece micrometer graduated in units = 0·031 millimetre. The measurements in this case are correct

<sup>1</sup> Etched balls of eutectoid composition do not give sharply outlined impressions.

within  $\pm 0.006$  millimetre, equivalent to  $\pm 4$  units in hardness number for 10-millimetre ball, and  $\pm 7$  units for 5-millimetre ball.

It is the author's opinion that such accuracy as just described is desirable in testing hardened steel. Measuring microscopes of less sensitiveness should not therefore be used for this purpose.

A conversion table giving Brinell numbers from 514 to 780 calculated upon diameter readings differing only by 0.001 millimetre has been added at the end of this paper. This table was computed by Mr. H. Sjövall.

#### MAGNETIC BALL HOLDER FOR BRINELL TESTS.

In Brinell testing machines the test ball is commonly held in position by a cap screwed on to the end of a stud, which transmits the pressure from the loading system to the test specimen. The ball fits into a suitable central recess in the stud end.

In order to facilitate replacement of the ball, which is of some importance when 5- and 10-millimetre balls are used alternately, the adoption of a permanent magnet as a ball holder instead of the stud and cap described has been suggested. This idea does not, however, work in practice, as stated by E. D. Campbell in the following words: "Magnetising the holder causes the ball to leave the depression and seek the edge of the holder."<sup>1</sup> This difficulty may be overcome by suitably shaping the end of the stud and enclosing it by a sleeve of non-magnetic material. A compound magnetic ball holder of such type designed to fit the Brinell press of A/B Alpha's construction is shown in Figs. 13 and 14. The magnet in this case was made of hardened ball steel (carbon 1.0, chromium 1.5 per cent.), the sleeve of aluminium bronze (aluminium 10 per cent.). The sleeve was pressed on to the tapered magnet with 4000 kilogrammes in order to prevent subsequent creeping between the two members. The end of the compound holder was then lapped to the shape shown in Fig. 14. It will be seen that there is a central spherical recess

<sup>1</sup> "Some Brinell Hardness Measurements on Small Specimens," *Transactions of the American Society for Steel Treating*, 1922, vol. ii. p. 271. Also "A Brinell Machine Attachment for Use with Small Specimens," *Journal of the Iron and Steel Institute*, 1922, No. II. p. 196.

for a 5-millimetre ball in the magnet, this recess being surrounded by a ring-shaped seat for the 10-millimetre ball formed partly in the magnet and partly in the sleeve.

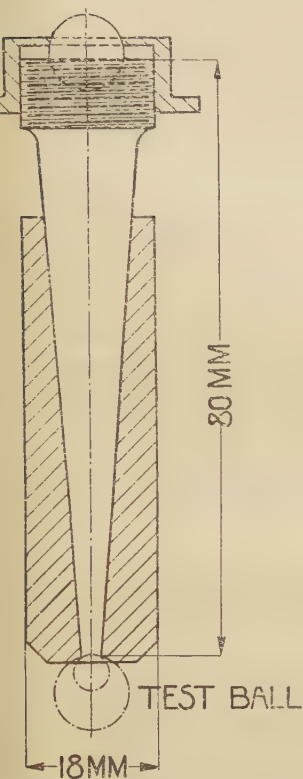


FIG. 13.—Magnetic Ball Holder for Vickers Hardness Testing Machine.

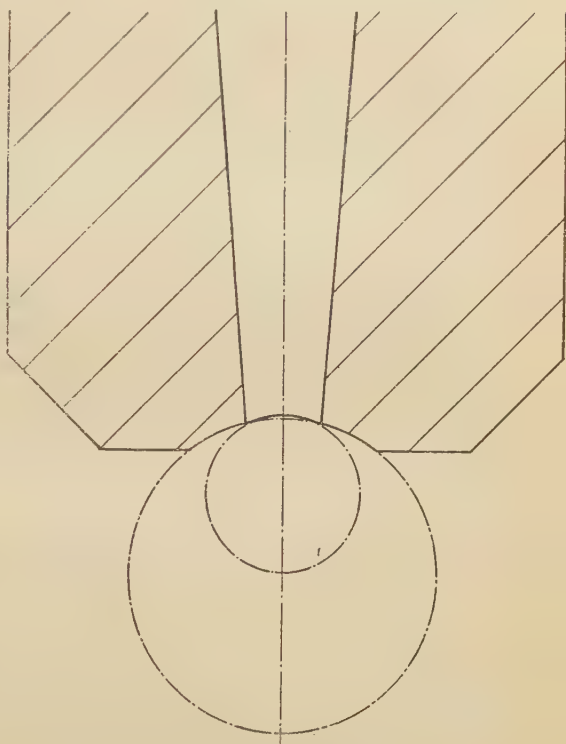


FIG. 14.—Detail of Fig. 13.

On account of the small depth of the ball seat and the pointed shape of the magnet the magnetic flux is concentrated at the centre and is strong enough to hold the ball securely in place, whether it be 5 or 10 millimetres. The sleeve in addition to supplying part of the supporting area for the 10-millimetre ball when under load also serves to reinforce the pointed end of the magnet that would otherwise be liable to burst. This device has proved efficient and convenient.

## SUMMARY.

A method of producing steel balls considerably harder than those heretofore available, and therefore especially suitable for Brinell tests on hardened steel, is described. The method consists in cold-working ordinary hardened polished steel balls. The surface portion is thus hardened to a sufficient depth to enable the ball to withstand considerably greater pressures than ordinary hardened steel balls do, without appreciable permanent deformation. By suitable etching, the depth to which the cold-working effect may be made to penetrate has been determined to be about 0.75 millimetre for 10-millimetre ball, and 0.4 millimetre for 5-millimetre ball.

A series of Brinell tests on hardened, as well as hardened and tempered steel specimens using different grades of 10-millimetre balls, including cold-worked balls, has been carried out in order to study the magnitude of the error in hardness number due to permanent flattening of the ball. The main results were : the error mentioned exceeds 1 per cent. when the material tested has a hardness number greater than

525 to 550 for ordinary Brinell balls ;  
 575 ,, 600 ,, special hard balls previously available ;  
 675 ,, 700 ,, cold-worked balls.

The surface hardness and strength of the cold-worked balls, as compared with those of other balls of different make and treatment, have been further studied by the following tests :

Martens scratch test ;  
 Herbert pendulum hardness test ;  
 Rockwell diamond cone hardness test ;  
 Deformation test ball against ball ;  
 Rebound test ; and  
 Crushing test ball against ball.

In all hardness tests used, with exception of the Martens and the Rockwell tests, the increased hardness due to cold-working manifested itself. An attempt is made to explain the exceptions.

The use of etched Brinell balls is suggested as a means of



increasing the accuracy of measuring the Brinell impression on hardened steel. In this connection it is recommended that the sensitivity of measurement of the Brinell microscope as commonly used should be increased.

A conversion table for Brinell numbers covering the high hardness range is given.

A magnetic ball holder for the Brinell machine is described.

The present investigation would not have been possible had not the manufacturing facilities of the A. B. Svenska Kullagerfabriken been freely placed at the author's disposal. For this, and for permission to publish the results, he is indebted to the directors of that company.

During the course of investigation he was materially assisted by the staff of the laboratory. He wishes especially to address his gratitude to Mr. H. Thorén for his careful assistance in many of the hardness determinations, and in the designing of apparatus for cold-working and rebound tests ; to Mr. H. Sjövall for computing the Brinell number table at the end of the paper, and for valuable suggestions in regard to the magnetic ball holder ; and to Miss E. Melander for assistance in the microscopical work.

*Brinell Hardness Numbers. (High Hardness Range.)*

For impressions made with 10-millimetre ball at 3000-kilogramme load.

 $d$  = diameter of impression in millimetres. $H$  = hardness number in kilogrammes per square millimetre.

$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .
2.200	780	2.250	745	2.300	712	2.350	682	2.400	653
1	779	1	744	1	712	1	681	1	653
2	778	2	743	2	711	2	681	2	652
3	777	3	743	3	711	3	680	3	652
4	777	4	742	4	710	4	680	4	651
5	776	5	741	5	709	5	679	5	651
6	775	6	741	6	709	6	678	6	650
7	775	7	740	7	708	7	678	7	650
8	774	8	740	8	707	8	677	8	649
9	773	9	739	9	707	9	677	9	649
2.210	772	2.260	738	2.310	706	2.360	676	2.410	648
1	772	1	738	1	706	1	676	1	647
2	771	2	737	2	705	2	675	2	647
3	770	3	736	3	704	3	674	3	646
4	770	4	736	4	704	4	674	4	646
5	769	5	735	5	703	5	673	5	645
6	768	6	734	6	702	6	673	6	645
7	767	7	734	7	702	7	672	7	644
8	767	8	733	8	701	8	672	8	644
9	766	9	732	9	701	9	671	9	643
2.220	765	2.270	732	2.320	700	2.370	670	2.420	643
1	765	1	731	1	699	1	670	1	642
2	764	2	730	2	699	2	669	2	641
3	763	3	730	3	698	3	669	3	641
4	763	4	729	4	698	4	668	4	640
5	762	5	728	5	697	5	667	5	640
6	761	6	728	6	696	6	667	6	639
7	761	7	727	7	696	7	666	7	639
8	760	8	726	8	695	8	666	8	638
9	759	9	726	9	695	9	665	9	638
2.230	758	2.280	725	2.330	694	2.380	665	2.430	637
1	758	1	724	1	693	1	664	1	637
2	757	2	724	2	693	2	664	2	636
3	756	3	723	3	692	3	663	3	636
4	756	4	723	4	691	4	662	4	635
5	755	5	722	5	691	5	662	5	635
6	754	6	721	6	690	6	661	6	634
7	754	7	721	7	690	7	661	7	633
8	753	8	720	8	689	8	660	8	633
9	752	9	719	9	689	9	660	9	632
2.240	752	2.290	719	2.340	688	2.390	659	2.440	632
1	751	1	718	1	687	1	658	1	631
2	750	2	717	2	687	2	658	2	631
3	750	3	717	3	686	3	657	3	630
4	749	4	716	4	686	4	657	4	630
5	748	5	716	5	685	5	656	5	629
6	748	6	715	6	684	6	656	6	629
7	747	7	714	7	684	7	655	7	628
8	746	8	714	8	683	8	655	8	628
9	746	9	713	9	683	9	654	9	627
2.250	745	2.300	712	2.350	682	2.400	653	2.450	627

*Brinell Hardness Numbers. (High Hardness Range)—continued.*

For impressions made with 10-millimetre ball at 3000-kilogramme load.

 $d$  = diameter of impression in millimetres.

H = hardness number in kilogrammes per square millimetre.

$d$ .	H.	$d$ .	H.	$d$ .	H.	$d$ .	H.	$d$ .	H.
2.450	627	2.500	601	2.550	578	2.600	555	2.650	534
1	626	1	601	1	577	1	555	1	534
2	626	2	600	2	577	2	554	2	533
3	625	3	600	3	576	3	554	3	533
4	625	4	600	4	576	4	554	4	533
5	624	5	599	5	575	5	553	5	532
6	624	6	599	6	575	6	553	6	532
7	623	7	598	7	575	7	552	7	531
8	623	8	598	8	574	8	552	8	531
9	622	9	597	9	574	9	551	9	531
2.460	621	2.510	597	2.560	573	2.610	551	2.660	530
1	621	1	596	1	573	1	551	1	530
2	620	2	596	2	572	2	550	2	529
3	620	3	595	3	572	3	550	3	529
4	619	4	595	4	571	4	549	4	528
5	619	5	594	5	571	5	549	5	528
6	618	6	594	6	570	6	548	6	528
7	618	7	593	7	570	7	548	7	527
8	617	8	593	8	570	8	548	8	527
9	617	9	592	9	569	9	547	9	526
2.470	616	2.520	592	2.570	569	2.620	547	2.670	526
1	616	1	591	1	568	1	546	1	526
2	615	2	591	2	568	2	546	2	525
3	615	3	590	3	567	3	545	3	525
4	614	4	590	4	567	4	545	4	524
5	614	5	589	5	566	5	545	5	524
6	613	6	589	6	566	6	544	6	524
7	613	7	588	7	565	7	544	7	523
8	612	8	588	8	565	8	543	8	523
9	612	9	588	9	565	9	543	9	522
2.480	611	2.530	587	2.580	564	2.630	543	2.680	522
1	611	1	587	1	564	1	542	1	522
2	610	2	586	2	563	2	542	2	521
3	610	3	586	3	563	3	541	3	521
4	609	4	585	4	562	4	541	4	521
5	609	5	585	5	562	5	540	5	520
6	608	6	584	6	561	6	540	6	520
7	608	7	584	7	561	7	540	7	519
8	607	8	583	8	561	8	539	8	519
9	607	9	583	9	560	9	539	9	519
2.490	606	2.540	582	2.590	560	2.640	538	2.690	518
1	606	1	582	1	559	1	538	1	518
2	605	2	581	2	559	2	538	2	517
3	605	3	581	3	558	3	537	3	517
4	604	4	580	4	558	4	537	4	517
5	604	5	580	5	558	5	536	5	516
6	603	6	580	6	557	6	536	6	516
7	603	7	579	7	557	7	535	7	515
8	602	8	579	8	556	8	535	8	515
9	602	9	578	9	556	9	535	9	515
2.500	601	2.550	578	2.600	555	2.650	534	2.700	514

*Brinell Hardness Numbers. (High Hardness Range.)*

For impressions made with 5-millimetre ball at 750-kilogramme load.

 $d$  = diameter of impression in millimetres. $H$  = hardness number in kilogrammes per square millimetre.

$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .	$d$ .	$H$ .
1.100	780	1.150	712	1.200	653	1.250	601	1.300	555
1	778	1	711	1	652	1	600	1	554
2	777	2	710	2	651	2	600	2	554
3	775	3	709	3	650	3	599	3	553
4	774	4	707	4	649	4	598	4	552
5	772	5	706	5	648	5	597	5	551
6	771	6	705	6	647	6	596	6	550
7	770	7	704	7	646	7	595	7	549
8	768	8	702	8	645	8	594	8	548
9	767	9	701	9	644	9	593	9	548
1.110	765	1.160	700	1.210	643	1.260	592	1.310	547
1	764	1	699	1	641	1	591	1	546
2	763	2	698	2	640	2	590	2	545
3	761	3	696	3	639	3	589	3	544
4	760	4	695	4	638	4	588	4	543
5	758	5	694	5	637	5	587	5	543
6	757	6	693	6	636	6	586	6	542
7	756	7	691	7	635	7	585	7	541
8	754	8	690	8	634	8	584	8	540
9	753	9	689	9	633	9	583	9	539
1.120	752	1.170	688	1.220	632	1.270	582	1.320	538
1	750	1	687	1	631	1	581	1	538
2	749	2	686	2	630	2	580	2	537
3	748	3	684	3	629	3	580	3	536
4	746	4	683	4	628	4	579	4	535
5	745	5	682	5	627	5	578	5	534
6	743	6	681	6	626	6	577	6	533
7	742	7	680	7	625	7	576	7	533
8	741	8	678	8	624	8	575	8	532
9	740	9	677	9	623	9	574	9	531
1.130	738	1.180	676	1.230	621	1.280	573	1.330	530
1	737	1	675	1	620	1	572	1	529
2	736	2	674	2	619	2	571	2	528
3	734	3	673	3	618	3	570	3	528
4	733	4	672	4	617	4	570	4	527
5	732	5	670	5	616	5	569	5	526
6	730	6	669	6	615	6	568	6	525
7	729	7	668	7	614	7	567	7	524
8	728	8	667	8	613	8	566	8	524
9	726	9	666	9	612	9	565	9	523
1.140	725	1.190	665	1.240	611	1.290	564	1.340	522
1	724	1	664	1	610	1	563	1	521
2	723	2	662	2	609	2	562	2	521
3	721	3	661	3	608	3	561	3	520
4	720	4	660	4	607	4	561	4	519
5	719	5	659	5	606	5	560	5	518
6	717	6	658	6	605	6	559	6	517
7	716	7	657	7	604	7	558	7	517
8	715	8	656	8	603	8	557	8	516
9	714	9	655	9	602	9	556	9	515
1.150	712	1.200	653	1.250	601	1.300	555	1.350	514

*DISCUSSION.*

Sir ROBERT HADFIELD, Bart., F.R.S. (Past-President), thought the author had given a most interesting and valuable paper, for which the members were greatly indebted to him, particularly as he had travelled such a long distance in order to present it personally to them. Mr. Hultgren stated on p. 201 that "Tempering of ordinary balls at  $150^{\circ}$  C. does not lower the rebound hardness, but perhaps slightly raises it, whereas tempering at  $225^{\circ}$  C. lowers the hardness to a marked extent." He thought it would be of interest if Mr. Hultgren could state the exact ball hardness, indicating how much the hardness had been lowered, which was of considerable importance. Mr. Hultgren had also given not only static tests but dynamic tests of hardened material tempered at  $150^{\circ}$  C., so that the members knew how much the toughness of the hardened material was increased by raising the tempering temperature to  $225^{\circ}$  C. Supposing the material was being tested in a shock machine, he would like to know the foot-pounds strength of the material tempered at  $150^{\circ}$  C. and also at  $225^{\circ}$  C., and the difference in the ball hardness at those two temperatures. He noticed that the author did not refer to anything much higher than 700, but Brinell referred, in some of his work, to a hardness of 800. Brinell had done a large amount of work in connection with hardness testing in Sweden, and the members of the Institute owed him an undying debt of gratitude, the results of his work being just as valuable to-day as nearly thirty years ago when he first brought forward his ideas on the subject. He hoped the author would convey to Dr. Brinell the thanks of a British audience for the valuable work he had carried out for the iron and steel industry throughout the world. Dr. Brinell had referred in some of his work to a ball hardness number of 800, but in a short conversation he (Sir Robert) had with Mr. Hultgren prior to the reading of the paper, the latter informed him that he did not quite expect such high ball numbers. He agreed with Mr. Hultgren that no accurate method of determining such high numbers existed. He thought, nevertheless, such high numbers did exist, although accurate methods of determining them had not yet been sufficiently perfected. Perhaps Dr. Rosenhain might have some suggestions to make on that point. He (Sir Robert) had offered a small prize to the Institution of Mechanical Engineers for the determining of high hardness, and useful work was done as a result, but definite information on the point was still required. Professor Turner carried out some most excellent work years ago with the scratch method of testing, but it could not definitely be said whether it was possible to obtain accurate hardness numbers much higher than 700. If it were possible to get 800 for certain purposes, then such material would prove to be superior in wear, resistance, and other advantages. He hoped Mr. Hultgren would be able to throw a little light on that point.



DR. WALTER ROSENHAIN, F.R.S. (National Physical Laboratory), said there were two points in connection with the paper which particularly interested him, the first relating to the question of the cold-working of hardened steel and the known influence of low-temperature tempering on steel. There was one way in which all the members were accustomed to the cold-working of hardened steel, namely, the stropping of a razor. He showed about 1906 that in stropping a razor an extremely thin piece of metal at the very edge was bent backwards and forwards, and there seemed little doubt about it that that thin film of hardened steel was cold-worked when a razor was stropped. There was some reason for thinking that tempering at  $100^{\circ}$  by holding it in boiling water had some effect, in course of time at all events. It was a well-known fact that cutting edges grew "tired" after long use, and if a razor were held in boiling water it had a beneficial effect.

There might be two kinds of cold-working in a hardened steel. One might be simply cold-working, such as was known to exist in other metals; in other words, the hardening process had not completely exhausted the mechanism of crystal slip and the material was further hardened by cold-working. The second was (and that was probably what occurred in the present case in which the amount of cold-working was slight) that, in a supersaturated solid solution in which a transformation was taking place, the precipitation was accelerated enormously by cold-working. It was well known that if certain austenitic steels were cold-worked they became martensitic. Again, Duralumin, which in the ordinary course took four days for hardening, could be quickly hardened by cold-working. The author's actual evidence of cold-working was extremely interesting, and of some considerable importance.

There was a small point of criticism he desired to make in connection with the paper. The dulling of the balls by etching was extremely convenient from the point of view of measuring an indentation, but did it not affect the reading? The Brinell number was in a sense a measure of the pressure which the material in the indentation could support. Ordinary considerations assumed that the pressure was normal to the surface of the indentation, and that implied no friction. Of course there was always some friction; but if the surface were deliberately roughened the friction was increased so much that he could not help thinking that the vertical component of the friction along the sloping sides of the indentation must slightly diminish the depth of the depression as compared with a smooth ball. He thought it was bound to have an effect, but whether it was measurable or not he did not know.

MR. E. G. HERBERT (Manchester) thought it might be interesting to the members to know that he had been measuring the work-hardening capacity of hardened steel with a pendulum. With the new work-hardening test made with a pendulum and with a diamond ball successive scale tests were made on the same spot, and he had found not

a slight work-hardening but a very considerable work-hardening on very hard steel. He had obtained curves of the change of the work-hardening capacity of hardened steel at a range of temperatures from cold to the temperature at which the steel began to soften.

Professor THOMAS TURNER (Birmingham) said he desired to refer to the scratch hardness test, as applied to very hard steels, for which materials more accurate methods were very desirable. During the past session a number of experiments on hardened steel had been made in his laboratory by Mr. Shires with specimens which Sir Robert Hadfield was kind enough to supply, and of which the ball hardness was known. They had reluctantly come to the conclusion that the scratch hardness test was not promising for very hard steels. Higher magnification was adopted in order to distinguish between the smaller scratches. The difficulty was that as the hardness increased the width of the scratch became smaller and smaller and the error became greater and greater, so that when the figure of about 650 ball hardness was passed, so far as they had gone at present at all events, the scratch hardness test became less and less trustworthy. He had made scratch hardness tests for many years, and he was sorry to have to make such a pessimistic report on the subject. The conclusion to be drawn, however, was that any other method, such as that which the author brought forward, which promised to give accuracy with great hardness, was worthy of most careful consideration.

Mr. AXEL HULTGREN, in reply to Sir Robert Hadfield's remarks respecting balls tempered at  $225^{\circ}$  as tested in the rebound test, said it would be seen from Table VIII. on page 202 that the rebound index for those balls was 9.7, whereas for balls tempered at  $150^{\circ}$  the rebound index was 8.5. With regard to the value of tempering at  $225^{\circ}$  from a practical point of view, it was his experience that if such balls were tested by crushing tests it might be possible to find an improvement in the crushing strength, but that did not mean that the balls would stand up better when used in ball bearings, for instance. There was probably, therefore, no benefit from such high tempering for practical purposes, although the toughness would be increased. He had not made any shock tests on balls so that he could not say anything on the point raised in that connection. With reference to the high Brinell numbers of 800 quoted in some of Dr. Brinell's literature, personally he had not met with any such high numbers in using a standard combination of 10 millimetres and 3000 kilogrammes. Perhaps some of those numbers were obtained with a 1000 kilogramme and 5 millimetre ball. That would explain part of the result, but otherwise he had no explanation to offer. With regard to the criticism offered by Dr. Rosenhain respecting the dullness on the actual value obtained in reading the diameter, that point had occurred to him and he had tried to make comparative tests. It was very difficult to do so because it was difficult, in testing hardened steels, to measure accurately the impression produced by the ordinary bright ball. He had not, however, been

able to find any difference outside of the experimental variation. He would reply to the further points in writing. In conclusion, he desired to express his thanks for the very kind reception given to his paper, and also to say that it would be a great honour to him to convey Sir Robert Hadfield's message of the gratitude of the Institute to Dr. Brinell for the work he had done.

### CORRESPONDENCE.

Colonel N. T. BELAIEV (London) wrote to congratulate the author on the very interesting research on increasing the hardness of the Brinell balls. He felt sure that if tested with such balls quenched steels would yield some very instructive results; the same would apply to some of the alloy steels, particularly to those of high cohesion. With reference to the proposed method of increasing the hardness of hardened articles by further cold-work, he would like to mention some of the methods lately in use at the Caucasus.

When studying various methods of sword manufacture, such, for instance, as the damascene method of India and the production of blades of the old Passau type in the Caucasus, he was told by some eye-witnesses of the current process (in the 'forties and 'fifties) of subjecting a finished and already heat-treated sword to a continuous but gentle hammering; the gentleman who related that procedure to him was struck by the patience of the smith, by the expenditure of time, and by the results. He was quite sure that the cutting properties of such swords were much in excess of the Western articles and of the damascene swords as well.

The latter statement was not very much to his (Colonel Belaiev's) liking, as he was very much absorbed in the damascene process and its possible revival. Coming, however, from an authority on swords, the statement appeared important, and now, in the light of the present paper, might be still interesting.

Mr. HULTGREN, in a further reply to the points raised during the verbal discussion, wrote that he thought Sir Robert Hadfield's question as to the exact amount by which the Brinell hardness of ordinary balls, not cold-worked, was lowered by tempering at  $225^{\circ}\text{C}$ . might be answered approximately by referring to Table V., where Brinell hardness values were given for the same hardened ring of ball-bearing steel tempered at four different temperatures, although that steel had not exactly the same composition as that used in the balls. By interpolating for a tempering temperature of  $225^{\circ}\text{C}$ . a Brinell number of 658 was obtained, the value for  $150^{\circ}\text{C}$ . tempering temperature being 695. As to the influence of tempering on the shock resistance of that type of material, he hoped to be able to supply that information later, after carrying out the necessary tests.

Sir Robert Hadfield also raised the important question as to the value and properties of very hard steels of about 800 Brinell, assuming that such material might be found. He (Mr. Hultgren) had not yet been able accurately to determine the Brinell hardness of the cold-worked surface layer of the balls described in his paper, that being rather difficult, because of the thinness of that layer. Judging from the various hardness tests on those balls, reported in the paper, such as deformation tests ball against ball, and rebound tests, it was very probable, however, that cold-worked hardened steel might possess such high hardness.

It was thought that the cold-worked balls might be more resistant to wear when used for Brinell tests on soft materials. One cold-worked and one ordinary Brinell ball were, therefore, used alternately on the same pieces of soft steel of a Brinell hardness of about 180. After 500 tests with each ball were made, the balls being kept in the same position all the time, the maximum wear as measured on the diameter was found to be about 0.001 mm. for both balls. Consequently, in that particular case, the wear resistance was not increased by cold-working.

He was much interested in Dr. Rosenhain's remarks. The stropping of a razor was not the only instance of cold-work applied to hardened steel. If a hardened and ground steel object, such as a ball-bearing ring, were examined under the microscope, signs of cold-work were generally seen at the surface. What the actual effect of cold-working hardened steel was, and whether a subsequent tempering at low temperatures was in any way beneficial for the cold-worked portions, might be an appropriate subject of further investigation. If Dr. Rosenhain would like to study those questions on cold-worked balls he (Mr. Hultgren) would be very glad to supply the material.

He wished to thank Dr. Rosenhain particularly for having called attention to the possibility that roughening of the ball surface by etching might not be harmless in that the increased friction produced between the ball surface and the specimen might affect the size of the indentation. He had now made additional tests to investigate that point. Three steel specimens of low, medium, and high hardness respectively were tested with bright as well as with etched balls, all cold-worked. The results were as follows, each figure being the average of four measurements :

Specimen.	Brinell Hardness Number, 10 Mm. per 3000 Kgs.	
	Bright Ball.	Etched Ball.
Soft . . . .	134	139
Medium . . . .	507	507
Hard . . . .	738	732



From the table it would be seen that there was no effect of increased friction visible in the Brinell value when medium and hard materials were tested, that was in the only cases when the use of an etched ball was justified for reasons of accurate measurement. The difference obtained on the soft material, however, was probably due to the cause suggested.

Mr. Herbert's brief remarks were very welcome. His determinations of the work-hardening capacity of hardened steel using his pendulum would be a valuable contribution to the subject dealt with in the present paper. It was to be hoped that his results would soon be published.

He thanked Professor Turner for his communication regarding the scratch test, and for his conclusion that the cold-worked balls promised to give accurate results on materials of great hardness. It was stated in the paper that by using balls made according to the process described accurate Brinell tests might be carried out up to about 675 Brinell. When materials of still greater hardness were tested the results would, of course, be more accurate than those heretofore obtained by Brinell's method, using ordinary balls, but still that was a field where further improvement was needed. It was to be hoped that by the use of some still harder ball material the upper limit might be brought to, say, 800 Brinell, thus maintaining the advantage of one scale of reference for the hardness of all metal articles. Recently introduced hardness testing methods, using a diamond cone or pyramid as indenting tool, were undoubtedly expedient and useful in giving accurate results on hard materials, but suffered from the uncertainty as to how those results could be translated into Brinell units.

He thanked Colonel Belaiew for his kind reference to the paper, and was most interested in his description of the hammering treatment as applied to the edges of swords manufactured in the Caucasus. Were those swords fully hardened to martensitic structure? If so, that was, to his (Mr. Hultgren's) knowledge, the only instance recorded, apart from the present paper, of subjecting fully hardened, high-carbon steel objects to cold-working for the express purpose of improving their hardness and related properties. It might be assumed that such hammering was only made possible by great care in the previous hot-working and heat-treatment operations.



## Iron and Steel Institute.

INVESTIGATIONS ON THE HERBERT  
PENDULUM HARDNESS TESTER.

BY CARL BENEDICKS AND VILHELM CHRISTIANSEN.

## 1. INTRODUCTION.

SINCE the introduction of steel balls for hardness testing, due to Brinell in 1900, two modes differing essentially from that of Brinell have been proposed for their use. The first is in Shore's scleroscope, which has won considerable popularity, although the use of small specimens occasions some errors not easily obviated.<sup>1</sup> The second is that used by Edward G. Herbert in an instrument of novel design, the Herbert pendulum hardness tester, which has lately been put on the market. This instrument possesses several new features, and permits of the use of even very small specimens, without taking any special precautions. For this reason a detailed investigation has been carried out at the Stockholm Metallographic Institute in order to gain some primary knowledge on the working of the new instrument, and also to compare its results with those of the Brinell method.

The instrument used was kindly placed at the authors' disposal by Messrs. Bergman and Beving, of Stockholm, representatives for Sweden of Edward G. Herbert, Ltd., Atlas Works, Levenshulme, Manchester. It was one of the heavier type, weighing 4 kilogrammes, and using steel balls only.

2. DESCRIPTION OF THE PENDULUM AND ITS  
DIFFERENT USES.

An arched casting A, the form and dimensions of which are shown in Fig. 1, is supported, on the plane surface of the specimen, by a small (1 millimetre) steel or ruby ball B, firmly held by a screwed chuck C. The centre of gravity of the arc can be brought to coincide with the centre of the ball by adjusting six balancing

<sup>1</sup> F. S. Tritton, *Journal of the Institute of Metals*, No. 2, 1921, p. 261.

screws,  $D_1$ ,  $D_2$ ,  $E_1 \dots F_2$ . The centre of gravity is then lowered a short definite length (0.100 millimetre) by displacing the

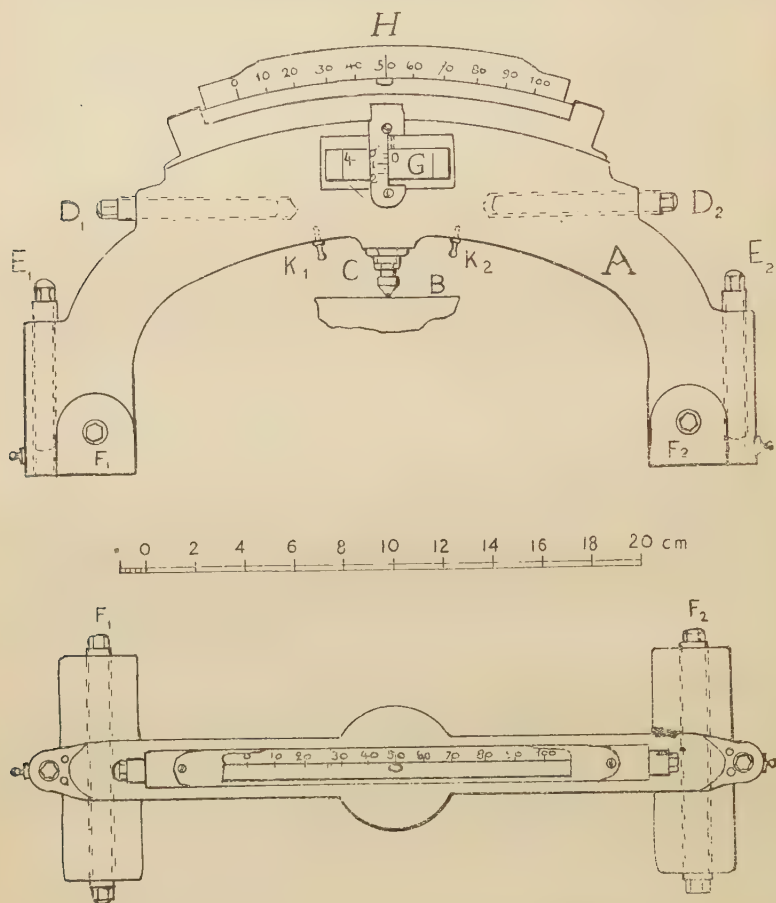


FIG. 1.

cylindrical weight  $G$ , mounted on a screw, from its zero position to a lower position, which is exactly obtained by using the graduations on the periphery of  $G$ . The instrument now constitutes a well-defined pendulum, the stable motion of which is read on a curved spirit-level  $H$ , provided with a scale which is graduated from 0 to 100.

On a standard glass plate the time of a single swing should be ten seconds. On a substance which is definitely indented by the ball, the time of oscillation is shortened; there also occurs a considerable damping. The instrument thus provides two independent tests of hardness: (1) The "Time Test," and (2) the "Scale Test." The time test, defined by the time of ten single swings as measured by a stop-watch, gives "indentation hardness." It is considered to correspond with the Brinell test, and time hardness numbers are easily converted into Brinell hardness numbers.

For the scale test the instrument is tilted until the bubble of the level reaches the one end, at 0, and is then placed on a level surface of the substance. When released, it will swing out to a definite position, which is read off on the scale. This is a function of the deformation work done by the ball on the specimen, and is said to measure its work hardness, or resistance to working with a tool, a property not measured by any other instrument. The ratio of scale to time hardness numbers measures "flow hardness," or resistance to flow, a quality which has not previously been isolated or measured.

### 3. THE MODE OF SWINGING OF THE PENDULUM.

It has been shown by photomicrographs, supplied by the inventor, that the ball of the pendulum when swinging on a metal surface makes elongated impressions in it. This, however, does not exclude the possibility of rotation of the ball as well, within the impression formed, with consequent friction. Knowledge on this point is of considerable importance for the theory of the pendulum.

From careful measurements of the diameters of the impressions shown in a series of photomicrographs supplied by the inventor, the following result was obtained for the difference  $D-d$  (Fig. 2), corresponding to the elongation of an impression due to the motion of the pendulum:

$D-d$ observed	0.104 : 0.220 mm.
„ calculated under the assumption of a purely rolling motion	0.108 : 0.216 „

It may safely be concluded that the motion of the pendulum ball on a non-elastic specimen is a rolling, not a sliding, one.

As the eventual tendency for sliding must be considered as being even more likely to occur in the case of a permanent indentation than in the case of an elastic deformation, we further seem justified in concluding that, generally, the motion of the ball of the Herbert pendulum is purely one of rolling.

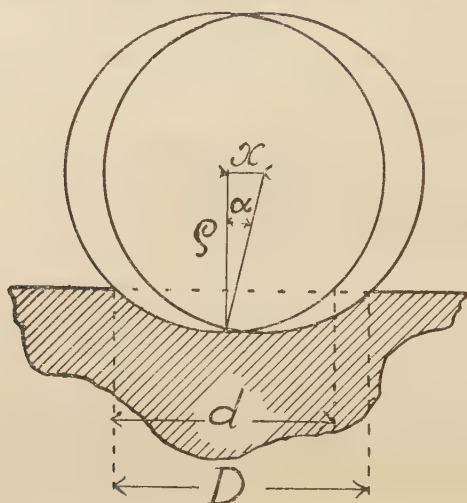


FIG. 2.

This is of interest, as there has been much discussion on the question whether the edge which supports a precision pendulum is to be considered as partly rolling and partly gliding.<sup>1</sup>

#### 4. GENERAL INFLUENCE OF THE SUPPORTING MEDIUM.

It is obvious in the scale test that the decrease in amplitude is due to the expenditure of energy at the contact between the ball and the metal surface: the greater the amount of cold-working, the sooner the motion of the pendulum is arrested.

On the time test, however, the reason of the shortening of the oscillation period is not obvious; so in the pamphlet descriptive of the instrument nothing is mentioned regarding this fundamental question.

<sup>1</sup> Ph. Furtwängler, "Enc. d. matem. Wissenschaften," Bd. IV. : 1, II. (Leipzig, 1904), p. 22.

In order to elucidate this point, let us first consider the motion of the pendulum on a plane hard surface A (no deformation being assumed), Fig. 3. O denotes the suspension ball in its zero position, the centre of gravity of the pendulum being at  $P_0$ . Now, if the kinetic energy,

$$\frac{I}{2} \left( \frac{d\phi}{dt} \right)^2$$

is imparted to the pendulum, where  $I$  = momentum of inertia, the pendulum will swing out a definite angle  $\phi$ , corresponding

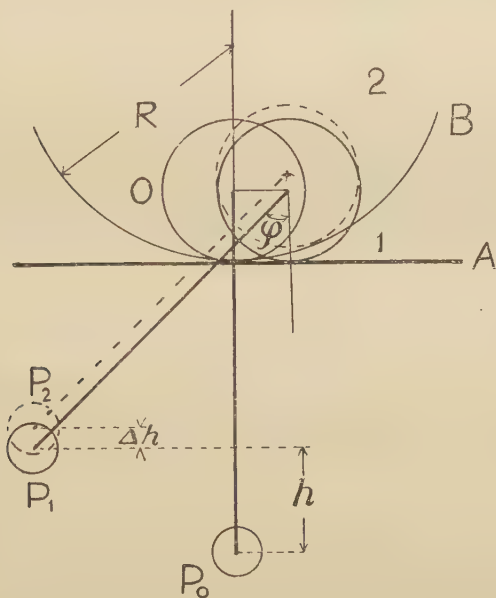


FIG. 3.

with the gravity point, being displaced until it reaches the point  $P_1$ , or raised the distance  $h = l(1 - \cos \phi)$  ( $l$  = distance between centre of ball and centre of gravity). The ball then assumes the position 1. The potential energy thus formed then passes into kinetic energy, and so forth.

Now, if the ball does not actually roll on the plane surface A, but on a curved surface B, its position, corresponding with the same angle  $\phi$ , will be that marked 2 instead of 1. This means



that the centre of gravity has now been raised a vertical distance  $\Delta h$ , higher than in the case of the plane surface. The reaction, which tends to bring the pendulum back in its zero position, thus evidently is increased. Making the calculation of the pendulum motion in the ordinary way, it will be found that the oscillation time is lessened in proportion as the radius of curvature  $R$  becomes smaller.

In order to demonstrate this fact—though it may be obvious in itself—a light “hardness pendulum” was made by bending a 10-millimetre lead rod (length, 265 millimetres; weight, 230 grammes) to a semicircle and inserting in a hole in the middle a short glass rod, ending with a glass ball 1.70 millimetre in diameter.

This pendulum was allowed to swing, first on a plane glass and then successively on the inner side of two short glass tubes (of known radius  $R$ ), which had been opened by cuts parallel to the axis; the swinging plane was at right angles to the axis.

Table IA. gives the values obtained on measuring the time, corresponding with four single swings.

TABLE IA.—*A Pendulum Swinging on Concave Cylindrical Glass Surfaces.*

2R mm.	Time per Four Swings. Secs.	Mean.	Time per Single Swing. Secs.
$\infty$	10.6	...	...
”	10.6	...	...
”	10.5	10.56	2.64
7.2	9.2	...	...
”	9.0	...	...
”	9.1	9.1	2.28
2.70	6.2	...	...
”	6.3	...	...
”	6.2	6.23	1.56

Thus it is evident that the time of oscillation of a given hardness pendulum decreases considerably with decreasing radius of curvature of the specimen.<sup>1</sup>

<sup>1</sup> This difference is not due to any different quality of the glass used. In fact, it is shown later on that different plane glass specimens give the same result.

Some tests along the same line were also carried out with the Herbert pendulum. By means of rotating Arkansas spheres (diameters, 1.5 to 3.5 millimetres; dental tools), small, nearly spherical indentations were made on a glass plate. The numbers obtained are given in Table IB.

TABLE IB.—*Herbert Pendulum on Spherical Glass Surfaces.*

2R mm.	Time per Ten Swings. Secs.
$\infty$	99.8
$\sim 3.5$	37.0
...	22.8
$\sim 1.5$	14.0

We may infer from this that the *decrease in the time test-number* which is found for the various metals is due to the fact that *the softer the metal the more the depth of the indentation increases.*

## 5. DEVICE USED FOR HANDLING THE PENDULUM.

In order to arrive at results as reliable as possible, and as it is not quite easy to place the instrument accurately at a desired place without shock, a special device—which much facilitated accurate work—was built up, using the regular laboratory stand fittings.

Between two rods, screwed in the same triangular base, a horizontal stem B could be turned through a small angle by means of the screw of the clamp C, as seen in Fig. 4. On B were fixed two horizontal stems, A<sub>1</sub> and A<sub>2</sub>, provided with a conical hole, respectively with a groove, parallel to the axis of B. In these the pendulum rested; for securing a well-defined position, two small pegs, K<sub>1</sub> and K<sub>2</sub> (Fig. 1), were screwed into the pendulum, symmetrically on both sides of the chuck. As after this addition the weight of the instrument was 4004.28 grammes, some lead was drilled off from the adjustment lead recesses provided on the instrument, until the weight was 3999.99 grammes, or practically the standard value. This slight addition to the instrument—which rendered the work more convenient than otherwise—

can therefore have no sensible influence on the readings of the pendulum.

As it is desirable to be able to locate the pendulum ball on the specimen with some precision, the following simple device was made, and was found to work well. A thin brass disc—say

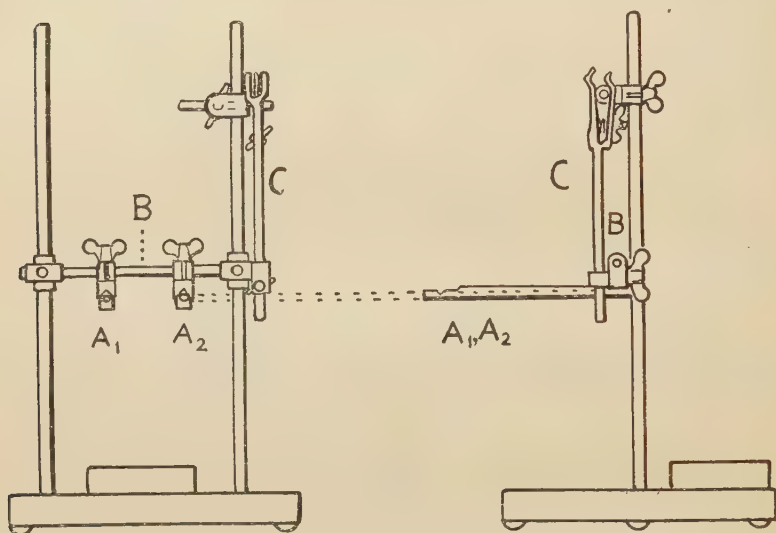


FIG. 4.

6 millimetres in diameter—is provided with a central concave hole, giving a thin sharp edge at the bottom surface. This little proving ring is placed, using a magnifying glass, on a point considered suitable for testing. It is then easy to locate the ball in its centre. The ring is wide enough not to touch the pendulum in its motion.

#### 6. ADJUSTING FOR NEUTRAL (INDIFFERENT) EQUILIBRIUM.

In order to get the pendulum properly adjusted, one of the two following methods is recommended. Place the instrument on a carefully levelled glass plate, and adjust the balancing screws so as to obtain a nearly neutral or indifferent balance; then lower the centre of gravity 0.1 millimetre—as has already been said. Alternatively, place the instrument on the glass plate supplied

with it, and adjust the time of ten swings to 100 seconds. From a physical point of view the first method of adjusting is decidedly preferable, as having a more absolute character.

The results obtained in a series of determinations, where the adjustment for neutrality was repeated seven times (and the weight then lowered as prescribed), are given graphically in Fig. 5. The glass plate, supplied with the instrument, is desig-

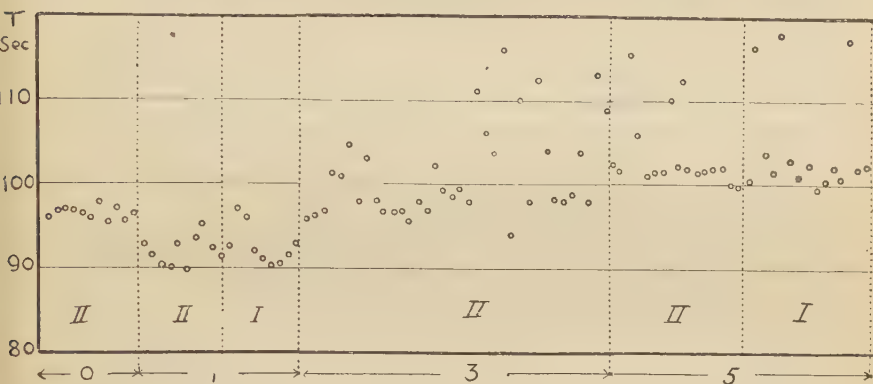


FIG. 5.

nated as I, while another spare glass plate (6.5 millimetres thick) is designated as II. Each series after a new adjustment is numbered 0, 1 . . . 6, of which, however, only series 0, 1, 3, and 5 are reproduced in the figure.

It will be seen, first, that no difference can be traced between I and II, and further, that the difference brought about by a new adjustment is clearly to be seen; this difference, however, is not much greater than the variation in the case of the adjustment being untouched.

## 7. FURTHER FACTORS INFLUENCING THE NEUTRAL EQUILIBRIUM ADJUSTMENT.

The adjusting for neutral equilibrium is rendered easier if the cylindrical weight be not at once placed at its zero position, but allowed to have a lower position, which is then successively, after a first adjustment, raised to the final position. This adjustment is

rather tedious, even if the glass surface be kept carefully cleaned. Not infrequently the pendulum is in equilibrium for very small swings, but unstable for larger swings. Two distinct factors were found to influence the adjustment to neutral equilibrium.

The first is a slight elastic deformation of the arch. The range in which it is possible to obtain neutral equilibrium is very restricted, on account of the elastic deformations of the pendulum. Thus the adjustment for neutrality will be much easier if the pendulum can be given greater rigidity.

Further, it was found, by means of a special series of observations, that the pendulum is sensibly affected by one-sided heating. Thus, an incandescent lamp placed on one side gives rise to a slight but continuous alteration of the adjustment.

Further, a detailed analysis was made of the motion of the pendulum on the glass plate used for the adjustment.

In order to save space, however, the Publication Committee has deemed it necessary to exclude the full account of this work from the present paper, but a few items must be referred to here.

The pendulum ball, when swinging on glass, gives rise to circular (conical) cracks in the glass; occasionally fragments are detached from the surface, and irregularities appear, generally causing an increased swinging time.

It is advisable to use small swinging amplitudes on setting the instrument—such as that of 10 divisions recommended by the fabricant. It was found, however, that even so high amplitudes as 40 can be used without materially altering the swinging time; though, then, too high stray values will occasionally appear—but they should be excluded from the mean value. It is necessary to wipe the glass surface *and the ball* very carefully if an accurate result is to be obtained. The individual variations then scarcely surpass 1.0 to 1.4 per cent.

A considerable number of different glass specimens, including the extra hard durobax glass (Jena), were found to give practically the same time value ( $100 \pm 1$ ); on rock crystal, however, a lower time value (95.6) was obtained, and on diamond a still lower one (92).

A detailed account of these experiments will appear in *Jernkontorets Annaler* (Swedish).



### 8. TEST ON DIFFERENT METALS ; RELATION BETWEEN TIME TEST AND BRINELL NUMBERS.

In order to ascertain the connection between time hardness numbers and Brinell hardness numbers, a series of different materials was tested. The comparative tests have been executed on a number of steel samples of different carbon contents, forged, annealed, and hardened, part of the original material used in a previous work.<sup>1</sup>

Further, a determination was carried out on a steel gauge of the C. E. Johansson, Eskilstuna, as well as on the exceptionally hard steel balls, obtained by the S.K.F., according to a new method worked out by A. Hultgren in Gothenburg.

In order to obtain specimens of widely different hardness qualities, tests were also made on a series of different alloys, the composition of which were not accurately known. Most of them were specimens kindly presented to the Institute by the Svenska Metallverken Company, Västerås.

The lower the hardness of the material to be tested, the sooner are the swings of the pendulum damped. At a given hardness of material the swings become so small as not to be observable with the required accuracy, and on less hard material they are apt to cease entirely. For the pendulum apparatus tested here (weight, 4 kilogrammes) the lower limit of its use was the hardness which corresponds with about fifteen seconds per ten swings.

The Brinell numbers of the bulk of the steel specimens were accurately known by previous work, already referred to. The Brinell numbers of the alloys were generally determined with a 5-millimetre ball and 500-kilogramme load. The Brinell numbers obtained with a 5-millimetre ball and a pressure of 500 kilogrammes, as was shown by one of the authors, do not differ by more than 0.5 per cent. from the regular Brinell numbers obtained with a 10-millimetre ball, at a load of 3000 kilogrammes.<sup>2</sup>

A synopsis of the results obtained is given in Tables II. and III. Here T signifies the time for ten swings ; four independent determinations were generally made with a number of ten swings.

<sup>1</sup> C. Benedicks, "Recherches physiques et physico-chimiques sur l'acier au carbone." Upsala, 1904. *Jernkontorets Annaler*, 1906, I.

<sup>2</sup> *Loc. cit.*, p. 87.

TABLE II.—*Hardness Tests on Different Steels.*

Glass : T = 100 ; S = 97.

Material.	O.	B.	T.	S.	$\frac{S}{T}$
Electro steel, Gysinge 1·1 .	0·08	83	14·7	10·3	0·70
"    "    1·2 .	0·08	146	19·3	27·8	1·44
"    "    1·3 H <sup>1</sup> .	0·08	126	20·3	34·3	1·69
"    "    2·1 .	0·45	178	22·8	44·8	1·97
"    "    2·2 .	0·45	239	27·0	44·3	1·64
"    "    2·3 H .	0·45	427	36·3	58·0	1·60
"    "    3·2 .	0·55	246	29·0	43·3	1·49
"    "    3·3 H .	0·55	434	35·4	58·3	1·65
"    "    4·1 .	0·90	204	24·2	41·8	1·73
"    "    4·2 H .	0·90	683	69·7	83·0	1·19
"    "    5·1 .	1·20	190	23·5	43·0	1·83
"    "    5·2 .	1·20	238	27·5	47·0	1·71
"    "    5·3 H .	1·20	687	77·5	92·5	1·19
"    "    6·1 .	1·35	197	23·4	42·0	1·87
"    "    6·2 .	1·35	263	28·4	49·5	1·74
"    "    6·3 H .	1·35	681	62·4	84·3	1·35
"    "    7·1 .	1·50	181	22·1	42·5	1·92
"    "    7·2 .	1·50	276	31·6	52·0	1·64
"    "    7·3 .	1·50	178	22·4	42·5	1·90
"    "    8·1 .	1·70	185	24·1	46·3	1·92
"    "    8·2 .	1·70	231	27·7	51·5	1·86
Bessemer steel, Långshyttan .	0·10	124	16·9	26·0	1·54
"    "    " .	0·15	142	18·2	34·3	1·89
"    "    " .	0·20	149	17·0	34·5	2·03
"    "    " .	0·25	135	19·9	41·8	2·10
"    "    " .	0·30	166	21·3	41·8	1·96
"    "    " .	0·35	146	21·0	39·5	1·88
"    "    " .	0·40	219	24·0	44·3	1·85
"    "    " .	0·45	165	24·6	45·0	1·83
"    "    " .	0·50	145	20·9	43·0	2·05
"    "    " .	0·55	139	21·0	42·5	2·02
"    "    " .	0·60	146	22·5	43·5	1·93
"    "    " .	0·65	208	23·7	44·0	1·86
"    "    " .	0·70	227	25·4	47·0	1·85
"    "    " .	0·75	258	26·9	49·3	1·83
"    "    " .	0·80	256	27·6	47·5	1·72
"    "    " .	0·85	272	30·3	51·5	1·70
"    "    " .	0·90	275	30·7	50·3	1·64
"    "    " .	1·00	301	32·8	54·3	1·66
"    "    " .	1·10	333	33·0	58·0	1·76
"    "    " .	1·20	293	30·9	55·8	1·81
"    "    " .	1·30	289	30·9	52·5	1·70
"    "    " .	1·40	318	32·4	54·8	1·69
"    "    " .	1·50	282	30·6	54·0	1·76
"    "    " .	1·60	345	33·2	59·2	1·78
"    "    " .	2·10	336	34·5	55·3	1·60
Steel gauges, C. E. Johansson.	...	...	78·6	93·8	1·19
Steel ball, "extra hard" S.K.F.	...	...	...	...	...
polished . . . . .	...	...	99·8	87·3	0·88
Steel ball, etched S.K.F. . .	...	...	99·7	85·8	0·86
Ordinary steel ball . . . . .	...	...	96·9	88·3	0·91

<sup>1</sup> H = hardened.

S is the scale test and B the Brinell number; C = carbon content.

The content of Tables II. and III. is reproduced graphically in Fig. 6. For the sake of comparison, the results which are

TABLE III.—*Hardness Tests on Different Materials.*

Glass : T = 100 ; S = 97.

Material.	B.	T.	S.	$\frac{S}{T}$
Lead . . . . .	4.7	...	0.0	...
Tin . . . . .	...	...	1.0	...
Bearing metal "Drakmetall"; AB Svenska Metallverken, Västerås,				
No. 1	17	...	6.8	...
"    "    "    No. 2	31	...	10.3	...
"    "    "    No. 3	24	...	6.6	...
"    "    "    No. 4	24	...	5.0	...
"    "    "    No. 5	29	...	4.8	...
"    "    "    No. 6	37	...	12.3	...
Zinc . . . . .	61	13.8	6.3	0.46
Tombac . . . . .	66	13.1	6.3	0.48
Aluminium-bronze, 94 per cent. alu- minium, 6 per cent. copper . . . .	71	14.8	9.8	0.66
Brass for spinning 62 per cent. copper .	86	15.0	9.0	0.60
Brass for cartridges "28B," 72.7 per cent. copper . . . . .	...	12.5	7.8	0.62
Brass for cartridges "28," 72.7 per cent. copper . . . . .	...	21.9	39.0	1.78
Brass unannealed, 72.7 per cent. copper	152	21.7	32.5	1.50
Patent nickel (20 Pfennig coin) . . .	128	18.4	9.5	0.52
Duralumin . . . . .	133	23.4	28.0	1.20
Aluminium-bronze, "Dirigold" . . .	167	26.3	47.3	1.80
Monel metal . . . . .	204	24.8	48.8	1.97
Era manganese steel (Hadfield) . . .	312	28.0	59.0	2.11
Nichrome . . . . .	294	32.0	60.3	1.89
Celluloid . . . . .	...	24.8	12.0	0.48
Ebonite . . . . .	...	28.0	37.3	1.33

given in the Herbert descriptive pamphlet are reproduced on the same scale in Fig. 7. As will be seen, the accord must be said to be fairly good.

It may be observed that the three highest values in Fig. 6, viz. those for hardened steel, differ widely.

As a matter of fact, the Herbert tests varied considerably at different points of the hardened specimens; the lapse of time

between the Brinell determinations and the present tests might also to some extent be responsible for this irregularity.

For the sake of comparison, in Fig. 7 the graphical representation has been plotted (I) of the two formulæ proposed by

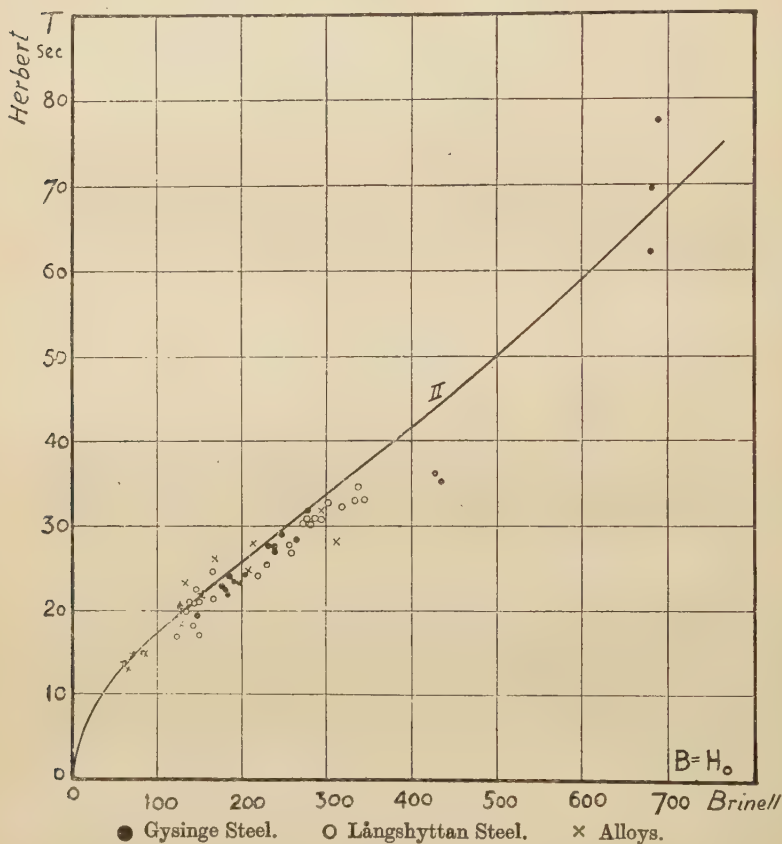


FIG. 6.

Herbert for converting the time test-numbers into Brinell numbers, viz. :

$$\begin{aligned} B &= 0.3T^2, \text{ when } T < 33.33, \\ \text{and} \quad B &= 10T, \text{ when } T > 33.33. \end{aligned}$$

As will be seen from the figures, these formulæ represent the actual observations, including those now obtained, with fairly

good accuracy. However, it cannot be denied that the discontinuity assumed—that is, the validity of two different functions on both sides of the values  $T = 33.33$ —is entirely gratuitous. There is no reason for not admitting the connection between  $B$  and  $T$

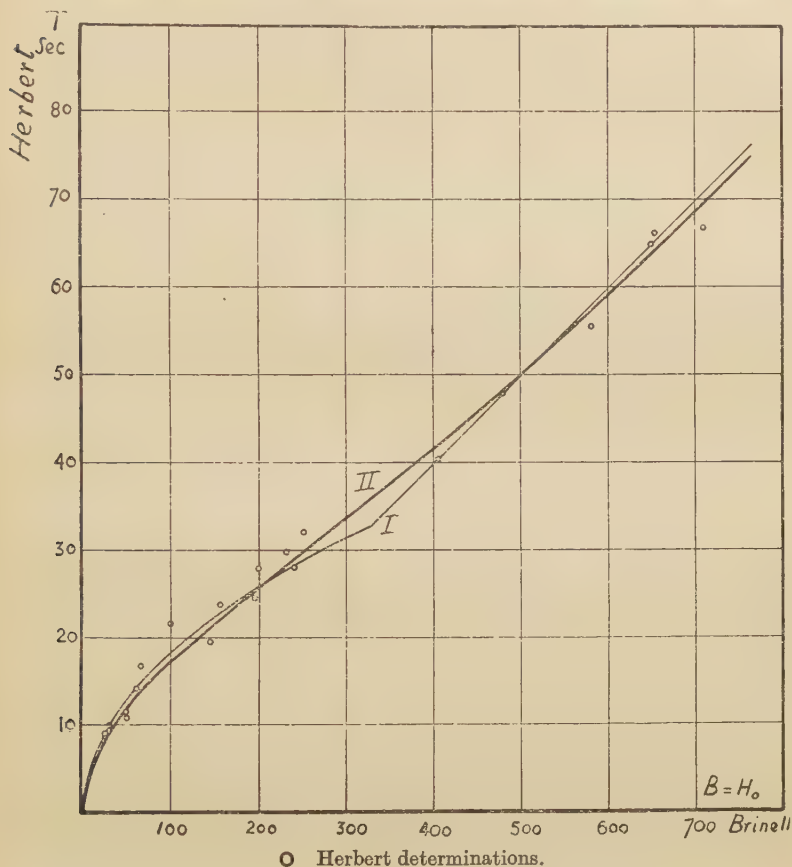


FIG. 7.

to be a continuous function, as the continuous curve (II) drawn in Fig. 7 (and in Fig. 6).

The—entirely empiric—formula of this curve is the following :

$$T = kB^{\frac{1}{2}} + hB^2;$$

for the constants are taken the values—

$$k = 1.7 \text{ and } h = 0.000047.$$



As will be seen, this curve comes very near to the observed points, so that on the whole no systematic deviations occur. It may be added that this curve contains only two constants, that is, not more than in Herbert's formulæ.

### 9. HARDNESS OF THE EXTRA HARD BRINELL BALL OF S.K.F.

A point of some special interest was to know if the Herbert pendulum permitted of a hardness measure on the extra hard steel balls of S.K.F., already referred to. In order to use the pendulum on these steel balls (10 millimetres in diameter) a special chuck was constructed, in which the ball was held firmly in a centred position. By means of a centring ring, fitting exactly on the upper surface of the chuck, and divided into two parts, so as to enable its withdrawal before the test, it was possible to place the pendulum with considerable accuracy on the highest point of the ball to be tested.

As will be seen from Table II., these balls gave a time test figure which scarcely differs from that of a glass plate. Of course the curvature of the steel balls will have the effect of slightly raising the figure. This, however, is the case also for the ordinary steel ball used as a standard, and we may conclude that the Herbert time test gives evidence of an increased hardness of the new steel balls of S.K.F.

No difference was to be found between the extra hard balls in polished and etched condition.

As for the scale test, the figures obtained for the extra hard balls are not higher than that obtained for the comparison ball, and they are decidedly lower than the value obtained for the hardened steel gauges of C. E. Johansson.

### 10. WORK HARDNESS AND FLOW HARDNESS.

It is stated in the descriptive pamphlet that "the scale test measures work hardness or resistance to working with a tool which is not measured by any other instrument." This ought to be "not directly measured by any other instrument." As a matter of fact, from a theoretical point of view, the result of the scale test must be practically the same as the increase in the

Brinell numbers obtained on increasing the load used. It can be said that while the scale test gives an indentation in one single direction (that of the swing), the Brinell test, on increased load, will make an increased "indentation" in all directions. As a measuring method the scale test might be preferred, but in point of principle the mode of working must be analogous. Thus, in the case of the scale test giving an exceptionally high value in relation to the time test, that is, at an exceptionally high value of the ratio  $\frac{S}{T}$ , or "flow hardness" (which is also included in Tables II. and III.), we must expect a considerable increase in the Brinell numbers on increasing the load.

In order to test this supposition, some Brinell tests were carried out on the metal which shows decidedly the greatest "flow hardness," namely, Era manganese steel. A Brinell series was also carried out on the sample of Monel metal used, which likewise has a very high ratio,  $\frac{S}{T}$ . The result is given in Table IV.

It will be seen from this that for Era steel the Brinell hardness number  $H$  (referred to spherical surface) *considerably increases* with increasing load  $P$ , both with the smaller 5-millimetre ball ( $H = 175$  to  $213$ ) and with the 10-millimetre ball ( $185$  to  $212$ ). Now, this increase being a general feature for most metals, one of the authors<sup>1</sup> has shown how to reduce the  $H$  values obtained, using different  $P$  to a standard value  $H_0$ , corresponding with a definite load  $P_0$  (as 500, or 3000 kilogrammes). Using the formula (2) given there, the above  $H$  values are reduced so as to be valid for the same pressure  $P_0 = 500$ , respectively  $P_0 = 3000$  kilogrammes. It will be seen from the last column in Table IV. that even these values  $H_0$  (designated also as  $B$ )—which generally are constant—for the Era steel, do increase with increasing load: using the 5-millimetre ball ( $193$  to  $213$ ) as well as the 10-millimetre one ( $205$  to  $212$ ).

Consequently, *for this material, Era steel, which is characterised by the highest "flow hardness," according to Herbert (2.11), there is a very marked increase in the Brinell number with increasing load.*<sup>2</sup>

<sup>1</sup> C. Benedicks, *loc. cit.*

<sup>2</sup> It is natural to admit that this increase is to a great extent due to a transformation of austenite into martensite.

This is exactly what was to be expected. It may be added that one of the authors<sup>1</sup> has shown earlier that the Brinell numbers for a ball  $2\rho = 5$  millimetres and  $P = 500$  kilogrammes are practically identical with those obtained with a ball  $2\rho = 10$  millimetres

TABLE IV.—*Brinell Tests on Increasing Load.*

Alloy.	$2\rho$ . mm.	P. kg.	$d$ . mm.	H.	$B = H_0$ . ( $P_0 = 500$ , resp. 3000 kg.)
Era manganese steel.	5	99.8	0.85	175	193
	5	199.6	1.16	186	200
	5	299.3	1.37	199	209
	5	399.1	1.58	199	204
	5	498.9	1.70	213	213
	10	1000	2.625	185	205
	10	2000	3.51	200	210
	10	3000	4.155	212	212
	5	99.8	0.80	197	218
	5	199.6	1.17	184	198
	5	299.3	1.39	193	203
Monel metal.	5	399.1	1.605	192	197
	5	498.9	1.79	193	193
	10	1000	2.625	182	202
	10	2000	3.56	194	204
	10	3000	4.51	178	178

and  $P = 3000$  kilogrammes (as used by Brinell). We see that this fact is borne out by the above determinations on Era steel, the corresponding figures being 213 and 212. This appears to be evidence of the reliability of these determinations or of the homogeneity of the steel investigated.

For the Monel metal, the result is much less conclusive. As will be seen, the H values slightly decrease with rising load  $P$  (197 to 193, 182 to 178, showing some irregularities); and the  $H_0$  values considerably decrease (218 to 193, 202 to 178). In this case the hardness number for the 5-millimetre ball and  $P = 500$

<sup>1</sup> C. Benedicks, *loc. cit.*, p. 87. The apparatus used above for  $P = 100$  to 500 is the same as that used in this thesis, while for  $P = 1000$  to 3000 a Brinell press from Aktiebolaget Alpha, Stockholm, was used.

kilogrammes ( $H = 193$ ) considerably differs from that obtained with the 10-millimetre ball and  $P = 3000$  kilogrammes ( $H = 178$ ). This is quite abnormal, and suggests that the Monel metal specimen used was not homogeneous, probably being harder near the surface than in the interior.

In any case, it has been established that for the material having the highest "flow hardness" of all, the Era manganese steel, one also finds an extraordinary high increase in Brinell hardness on increasing load.

In consequence, we seem to be justified in considering the qualities measured as "work hardness" and "flow hardness" respectively to bear a definite relation to the Brinell test. In other words, the time test, or indentation hardness, as stated already by Herbert, is very closely related to, and convertible into Brinell numbers; the scale test, or work hardness, is to be considered as being related to the pressure derivative of the Brinell hardness.

This point of view merits a much more detailed examination; no doubt the scale test, being a much more direct method than a series of Brinell tests, seems to be very promising for elucidating this subject.

## 11. SUMMARY.

1. A somewhat detailed scrutiny has been made of the construction and working of the Herbert pendulum hardness tester.

2. It has been established that the motion of the pendulum ball, on the swinging of the instrument, is a purely rolling (not sliding) one.

3. As evidenced by some direct proofs, the shortening of the time of oscillation for metals as compared with the swinging on glass is due to the general fact that the period is shorter on a concave surface than on a plane one; the effective curvature increases with the depth of indentation in the metal.

4. For handling the instrument a device was used (Fig. 4), which proved to be of great service.

5. It was found quite practicable by adjusting the pendulum for indifferent equilibrium, and then lowering the centre of gravity, to obtain fairly concordant values. The adjustment for

indifferent equilibrium, however, is rather tedious, on account of some slight elastic deformations of the pendulum casting (directly proved to occur). A somewhat increased rigidity of the arch would render the adjustment easier. As, however, no difference could be detected between widely different glass plates for the behaviour of the pendulum, there is scarcely any objection to be made against the—somewhat easier—direct adjustment of the pendulum, so as to give a time number 100 on glass.

6. A considerable number of different steels and other materials (including diamond) were tested, and partly compared with regard to Brinell hardness. The actual results obtained (Fig. 6) agree fairly well with those of Herbert.

The new “extra hard” Brinell balls made by the S.K.F. in Gothenburg (Hultgren’s method) were found to give time test-numbers slightly above those of ordinary steel balls.

7. As claimed by the originator, the “scale test” seems to offer considerable interest for the cold-working properties of metals. It was pointed out, however, and established for manganese steel, that the increase in the Brinell numbers, on increasing load, probably gives analogous results.

To sum up: The present investigations, besides elucidating some obscure points, lend support to the statements of the inventor, and lead to the conclusion that the Herbert pendulum is an interesting and useful addition to the metallographic laboratory.



*CORRESPONDENCE.*

Mr. EDWARD G. HERBERT (Manchester) wrote that while appreciating the careful nature of the investigations described in the paper, he could not help regretting that he was not aware that it was in preparation. A considerable body of data had been collected expressly for the purpose of assisting those desirous of investigating the theory of the instrument, and that material, consisting mainly of measurements and photographs of impressions made by the pendulum tests in various materials, he would gladly have placed at the disposal of the authors.

As regarded the theory of the time test, the authors had shown that a decrease in the radius of curvature of the impression must result in a more rapid oscillation. They had not shown any reason for believing that the impressions made by the same ball in hard and in soft materials were in fact different in curvature. As a result of careful measurements of time-test impressions it was possible to arrive at some quite definite conclusions.

The impression seen in plan was approximately circular—as nearly circular as a Brinell impression. There was no persistent elongation of the impression in the direction of oscillation. Seen in profile—that was, in a vertical section through the impression—the curvature was also approximately circular, and it followed that the surface of the impression was approximately spherical. The radius of curvature was about 30 per cent. greater than that of the ball. The impression made by the 1-millimetre ball would closely fit a ball 1.3 millimetre in diameter. The depth of the impression made by the time test in mild steel was about 0.0075 millimetre. His own conception of what occurred was as follows.

The ball in consequence of the slight oscillation of  $2^\circ$  or less rolled to and fro in the shallow impression which nearly fitted it, and as it rolled the point of contact between the ball and the impression travelled from one side of the impression to the other. At the extremity of an oscillation the point of contact, which was the point of suspension of the pendulum, was at the edge of the impression; the weight of the pendulum acted through the centre of the ball, which was virtually at the centre of the impression. There was therefore a gravitational moment equal to the weight of the pendulum multiplied by half the diameter of the impression, tending to restore the pendulum to its central position. If the specimen were soft there was a large impression, a large restoring moment, and therefore a quick swing. With a spherical impression it was not certain that the oscillations would be isochronous, as the amplitude became less through damping. A mathematician could no doubt find the equation of a curve which would give

isochronous motion, and that might be found to be a cycloidal curve closely approximating to the circular form.

If that theory were correct there should be a close relationship between the diameter of the impression and the time of swing, and such a relationship had been found to exist. If the diameter of the impression were measured in millimetres, the reciprocal of the diameter squared approximated to the number of seconds for ten single swings. The value so calculated was too low on soft materials and too high on hard substances.

A device for handling the pendulum, or rather for operating it entirely without handling, had been devised by the makers of the instrument.

For the purpose of converting the time hardness numbers into Brinell hardness numbers two formulæ had been developed, for hard and soft materials respectively. With the authors' statement that the assumption of discontinuity was "entirely gratuitous," he was unable to agree. In carrying out Brinell tests it was customary and necessary to adopt different loads for hard and soft materials respectively. It was sometimes assumed that the two series of numbers so obtained were continuous, though it was fairly well known that such was not the case. After making a large number of Brinell tests on a range of materials with both the 500 kilogramme and 3000 kilogramme loads, he came to the conclusion that to arrive at any one formula for converting the continuous series of pendulum hardness numbers into the two discontinuous series of Brinell hardness numbers would be impossible. That impossibility the authors claimed to have accomplished, and they were to be congratulated. The new formula was interesting, but from the standpoint of practical utility somewhat difficult to apply. The metallurgist in a hurry would perhaps decide that the best way to obtain the Brinell hardness number was to make a Brinell test, and probably he would be right.

On the subject of work-hardness and flow-hardness the authors said that "from a theoretical point of view the result of the scale test must be practically the same as the increase in the Brinell numbers obtained on increasing the load used." The theory was not explained and did not appear to be well supported by the facts quoted, which showed that the Brinell numbers decreased with increasing load in Monel metal.

The subject interested him (Mr. Herbert) because he had encountered a similar phenomenon in testing another metal, rustless iron. In that case also the Brinell numbers decreased with increasing load; a specimen gave Brinell hardness 136 with 500 kilogramme and 101 with 3000 kilogramme load. In the case of manganese steel he, like the authors, had found that the Brinell numbers increased with the load, but in an irregular manner, an increase of load actual reversing the order of hardness in some cases. He had no theory capable of explaining those discrepancies, but he suspected that they, and also the divergence

between the time and scale hardness numbers of certain materials, were all manifestations of the same phenomenon.

Recent researches had impressed on his mind that hardness in metals was not a static quality. Hardness was changed not only by the act of working a metal, but also by the act of testing its hardness. It was the realisation of that fact which led to the development of the "work-hardening test," in which the specimen was progressively work-hardened by the repeated rolling action of the ball and the "work-hardening capacity" of the metal was measured. It was significant that manganese steel, rustless iron, and Monel metal all had abnormally high work-hardening capacity, and there could be little doubt that the discrepancies in the Brinell numbers were caused by work-hardening in the process of testing.

It was easy to measure the work-hardening produced by the Brinell test. The work-hardening test could not be made in the actual Brinell impression on account of its curvature, but by grinding away the surface of the specimen until only a trace of the impression remained, it was possible to obtain a flat surface of metal which had been compressed by the Brinell ball. Since that metal had already been work-hardened to some extent, its remaining work-hardening capacity must obviously be less than that of the surrounding metal which had not been affected by the Brinell test. The difference between those two work-hardening capacities measured the work-hardening produced by the Brinell test.

Experiments made on manganese steel showed that the Brinell test with 500 kilogramme load work-hardened the metal up to 22 per cent. of its maximum work-hardening capacity, and that the test with 3000 kilogramme load work-hardened it to 51 per cent. of its capacity. In view of those facts it was not difficult to understand why the higher load gave a higher Brinell hardness number, but still gave no true indication of the work-hardening properties of the metal, as shown by its working properties and as measured by the pendulum hardness tester.

Mr. A. HULTGREN (Gothenburg) wrote that in stating on p. 222 that, "generally, the motion of the ball of the Herbert pendulum is purely one of rolling," the authors apparently had not considered the fact that when a ball rolled in a closely fitting groove the conditions of pure rolling were not fulfilled. In the general case, during rolling, there would be simultaneous sliding forwards at the sides of the groove near the edges, and sliding backwards at the bottom. Only at a certain distance from the bottom, depending on the distribution of pressure in the contact surface, would pure rolling occur. The frictional resistance occasioned by the sliding was one cause of the gradual reduction of amplitude during the course of a Herbert time test, that effect being, of course, more noticeable in testing soft materials.

The authors assumed that the bottom of the impression made by

the Herbert pendulum was curved in the longitudinal direction, that curvature increasing for softer materials, and explained in that way the lower time-test values obtained for such materials. They arrived at that conclusion by analogy. It would, however, be of interest if the authors could give some evidence to prove that such was actually the shape of the groove. How did the authors explain the formation of that curve?

Referring to the diagrams in Figs. 6 and 7, was it necessary to assume that the curve should pass through the origin? Further, bearing in mind that the high values recorded necessarily were uncertain—the Brinell as well as the Herbert time test values—on account of permanent flattening of the ball, it appeared that one straight line would fit the plotted points just as well as the curve given. As far as cold-worked hardened steel balls were concerned, it might be remarked that in his (Mr. Hultgren's) own experiments,<sup>1</sup> using a steel ball as a pivot, quite irregular and unreliable results were obtained, due to permanent flattening of the ball. He did not think, therefore, that the values given by the authors represented the true hardness of that material. A suspension ball of ruby or other hard material should be used for such a purpose.

Mr. HUGH O'NEILL (University of Manchester) wrote that the results of the authors' examination of the fascinating Herbert pendulum tester confirmed the experience of those who had previously handled it. If used with care, the tester was without doubt a sensitive instrument, and he (Mr. O'Neill) had made measurements of the hardness of different faces of single crystals of aluminium with its aid.<sup>2</sup>

As the authors remarked, the pendulum tester was more suited to the laboratory than to the workshop, but portability was a great point in its favour. It was also worthy of mention that the pendulum hardness of india-rubber was very low (sometimes zero)—a result which compared favourably with scleroscope and Brinell (ordinary method) values for that material.

The inventor stated that the "scale test" measured work-hardness or resistance to working with a tool. By the courtesy of Mr. E. G. Herbert he (Mr. O'Neill) was enabled to make some pendulum tests in 1923 upon two samples of 60 : 40 brass. The two brasses had been examined by Professor C. H. Desch,<sup>3</sup> and lathe tests, drill tests, and shop experience alike proved that they possessed very different degrees of machineability. No. 623 was much more difficult to work with a tool than No. 618, yet hardness tests which he (Mr. O'Neill) had carried out and reported below in Table I. did not show it.

<sup>1</sup> "Improvements in the Brinell Test on Hardened Steel, including a New Method of Producing Hard Steel Balls," *Journal of the Iron and Steel Institute*, 1924, No. II. p. 7.

<sup>2</sup> *Journal of the Institute of Metals*, 1923, No. II.

<sup>3</sup> *Journal of the Society of Chemical Industry*, July 1920.



TABLE I.—*Tests on 60 : 40 Brass.*

Hardness Tests.	No. 618. Drilling Time, 25 secs. (Desch).	No. 623. Drilling Time, 40 secs. (Desch).
Herbert "scale" number. :	28.5	28.0
Herbert "time" number. .	20.0	22.4
Brinell number. 2-millimetre ball, 20 kilogrammes . .	123	113

Tests of that type seemed to be of little value as indicators of machineability.

The authors had reported some Brinell tests on manganese steel, and had corrected the rising hardness numbers obtained at different loads to what they said should be a uniform value  $H_0$  by means of Professor Benedicks' formula. When the values of  $H_0$  obtained in that way showed a tendency to rise the conclusion was arrived at that manganese steel gave "an extraordinary high increase in Brinell hardness on increasing load" (p. 237). That conclusion was contrary to his (Mr. O'Neill's) experience, and the following figures of other workers showed that manganese steel was not extraordinary in that respect.

TABLE II.—*10-Millimetre Ball.*

Sample.	Brinell Hardness H. Test Load.			Rise of H with Load.	
	1000 Kg.	2000 Kg.	3000 Kg.		
Manganese steel .	188	200	203	15	Norbury and Samuel, <i>Journal of the Iron and Steel Institute</i> , 1924, No. I.
Chromium steel (No. 19) . .	192	202	210	18	
Manganese steel .	205	212	221	16	Batson, <i>Proceedings of the Institute of Mechan- ical Engineers</i> , April 1923.
Tool steel . .	224	247	256	32	
Manganese steel .	185	200	212	27	Present authors.

If the rise of the authors' value  $H_0$  were not due to the behaviour of manganese steel, it might be due to the Benedicks' correction formula itself. He suggested that that was the cause of the trouble, and he knew that many other workers would agree with him. If



the Benedicks' formula were accurate, the Meyer law of comparison for spherical indentations would be inaccurate. All recent work, however, confirmed the validity of Meyer's observations.

Professor BENEDICKS, in replying to the discussion on his paper, wrote that, in regard to the fundamental point, namely, the theory of the time test which he and Mr. Christiansen had tried to elucidate, Mr. Herbert remarked that the authors "had not shown any reason for believing that the impressions made by the same ball in hard and in soft materials were in fact different in curvature." That remark was quite true, but in fact the authors found it nearly evident that the curvature was less in a hard material; for hardened steel the impression, if any, was extremely shallow, while for lead the impression would approach the curvature of the ball. As the method used by Mr. Herbert of preparing sections of the copper-plated specimen, though elegant in itself, could scarcely be very accurate, he (Dr. Benedicks) had now made some optical measurements in order to decide whether the curvature of the impression was variable, or, as Mr. Herbert assumed, essentially constant for different metals. The method used was a direct optical one: parallel light falling on a spherical impression, as was well known, would be reflected to a focus (giving a sharp image of the source of light) at a distance  $f = R/2$  from the lowest point (centre) of the impression, where  $R$  was the radius of curvature. Using a weak objective, and no concentrating lens—so that the light could be considered as practically parallel—focusing was made successively on: (1) the centre of impression, (2) the plane surface, and (3) the reflected image of the source of light. Using four specimens with impressions immediately at hand, pertaining to the original research material, the following figures were obtained (in millimetres):  $a$  was the distance between the image and the plane surface,  $b$  the indentation depth, and  $f = a + b$ , the focal distance of the concave mirror.  $T$  was the time figure obtained earlier.

	T.	$a$ .	$b$ .	$f$ .	$2R$ .
Lead . . . .	$>>10$	-0.086	0.39	0.302	1.21
Tin . . . .	$>10$	+0.235	0.09	0.325	1.30
Zinc . . . .	13.8	+0.325	0.025	0.350	1.40
Patent nickel . .	18.4	+0.334	0.024	0.358	1.43

As would be seen from the last column, the diameter  $2R$  of the sphere of curvature of the impression, for tin, was 30 per cent. higher than the diameter of the ball (1.00 millimetre). That was quite in accord with Mr. Herbert's general statement, "The radius of curvature was about 30 per cent. greater than that of the ball." For the softer metal, lead, however, the radius was only 21 per cent. greater; for

the harder metal, zinc, it was found to be 40 per cent., and for the still harder fourth metal, 43 per cent. greater than that of the ball. Thus, the curvature of the impression was actually a function of the hardness of the specimen. That substantiated the explanation given by the authors as to the time test.

It might be added, however, that, apart from the point just mentioned, the conception now given by Mr. Herbert in reality scarcely differed from the view of the authors as given in the paper; considering the gravitational momentum must of course give the same result as considering the raising of the point of gravity of the pendulum.

The fact that the impression seen in plan was approximately circular was evident; however, to conclude from that that no elongation at all occurred seemed scarcely to be possible, according to the figures now given by Mr. Herbert, as differences or irregularities in diameter for a given metal occurred there which were much greater than the difference to be theoretically expected.

He was glad to learn that the makers of the instrument had now introduced a device for handling it, which certainly would add to its popularity.

Concerning the discontinuity assumed by Mr. Herbert at  $T = 33\frac{1}{2}$ —and not accepted by the authors—the following might be said. It was of course well known that in order to transform Brinell numbers of annealed carbon steel into tensile strength, a discontinuity had to be assumed at 0.5 or 0.6 per cent. carbon—as shown by Mr. G. Dillner in 1903. He (Professor Benedicks) entered in his Doctor thesis into a detailed discussion of that, and related facts. That discontinuity—shown also by several other properties—was explained by the ferronite hypothesis, implying a constitutional difference between the ferrite at low-carbon content  $< 0.50$  and that at higher carbon. Thus the relation between Brinell numbers and tensile strength might be expected to change at that critical carbon content; but, in his opinion, no such reason could be found for a discontinuity at  $T = 33\frac{1}{2}$ .

In reply to the remarks of Mr. Hultgren, Professor Benedicks wrote, that it was quite true that purely mechanical friction possibly occurred in some zones on the rolling motion of the ball. That friction—probably small in comparison with the work done in deformation—of course would contribute to the damping of the motion on soft materials, but could not explain the decrease in the swinging time. As evidence to prove that the curvature of the impression was increased with decreasing hardness of the metal, he had pleasure in referring to the above observations.

Mr. Hultgren rightly asked if it were necessary to assume that the curve in Figs. 6 and 7 should pass through the origin. The reason why the author thought it must—though scarcely convincing—was the following.

First, it would decidedly be violating the actually observed points, at least those given by Mr. Herbert, to deny such a tendency. Thus,

he thought, Mr. Herbert had been quite right from the observations to infer a quadratic relation  $B = KT^2$ , valuable at low  $B$  values, and implying

$$T = 0 \text{ for } B = 0.$$

From a theoretical point of view the question was a complicated one, since neither the Brinell nor the Herbert test, without supplementary conventions, had any definite meaning for  $B = 0$  and  $T = 0$  respectively.

In order that the Brinell test should have a definite meaning near  $B = 0$ , it was necessary to assume first that the ball should be made weightless, and, further, that the material tested, though extremely soft, had a certain rigidity, permitting its free surface to support the weightless ball when acted upon by a very small pressure.

In analogy, in order to attribute a definite meaning to the Herbert test near  $T = 0$ , it was necessary to assume first that the pendulum could be given as small a mass as might be desired, and, moreover, that the material, notwithstanding its softness, had a rigidity sufficient to support the pendulum ball and to offer a definite friction, causing no sliding to occur between the ball and the supporting material. That being supposed to be extremely soft, the impression was to be considered as having practically, or even completely, the same curvature as the ball. Thus, according to the assumptions made, no proper rolling could occur, the ball being simultaneously rigidly supported by a large spherical surface. That signified that the oscillation frequency of a light pendulum must be extremely great—*i.e.* that  $T$  would be nearly  $= 0$ , as under the same circumstances  $B$  would nearly  $= 0$ .

That extension of the theoretical parallel between Brinell and Herbert test, of course, would scarcely be in opposition to Mr. Hultgren's proposal to summarise the observed points with a straight line. The joint authors had already discussed that possibility, but found it less advisable from a theoretical point of view.

He (Dr. Benedicks) did not consider the theory of the time test as at all a complete one; as suggested privately by Mr. Herbert, not only the curvature, but also the diameter of the impression might have a considerable influence.

Professor Benedicks wrote in reply to the communication of Mr. Hugh O'Neill that the interesting figures in his (Mr. O'Neill's) Table I. induced him to make the following remarks.

Let it be assumed that the Brinell hardness of a metal (*e.g.* copper) increased continually with increasing content of a foreign metal (*e.g.* zinc), within a wide range of composition. A cutting test—such as the drilling test—would then show a definite optimum at some given content of the foreign metal: at higher contents the drilling time would increase on account of the increased hardness, which caused more considerable cutting work and a gradual wearing off of the cutting

edges; at lower contents the drilling time would increase on account of the softness of the metal, which implied a less good chip formation, a soft metal (as copper)—as well known to every mechanic—being apt to “smear.” In order, therefore, to permit of a higher cutting speed in screw manufacturing, the hardness (or brittleness) of a low-carbon steel, as was well known, was often intentionally increased by the addition of sulphur or phosphorus.

In consequence, with increasing hardness beyond that optimum hardness, the Brinell tests and drilling tests would vary in the same

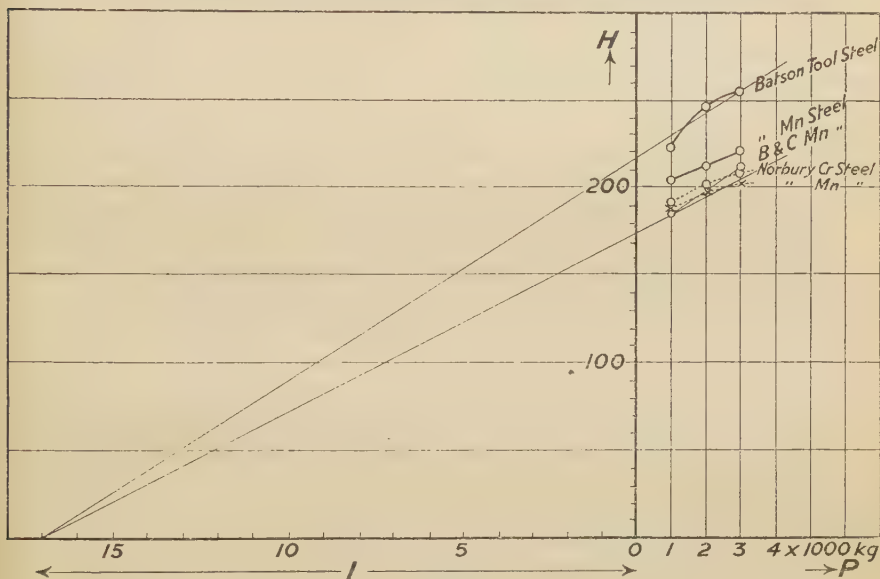


FIG. A.

direction, while below the optimum hardness Brinell tests and drilling tests would vary in an opposite direction. Apparently, the figures now quoted by Mr. O'Neill were valid for the latter case.

Table II. of Mr. O'Neill was of great interest, as showing that the Brinell hardness determination of some other workers on manganese steel did not show as great an increase of the hardness number  $H$  on increasing load  $P$  as that found by the authors. It was not known whether the specimens used by those other workers showed the same high “work hardness”  $S/T$  as the specimen used by the present authors (and obtained from Sir Robert Hadfield). Anyhow, a graphical reproduction now made by Professor Benedicks (Fig. A) gave evidence that the variations in  $H$  were so considerable that no definite conclusion as to an abnormally high increase in  $H$  with  $P$  now appeared to him to be

possible. The differences found by the different workers must be due to experimental errors, which, however, did not surpass about 5 per cent. They were in no way due to a supposed inexactitude of his (Professor Benedicks') reduction formula. As a matter of fact, that reduction implied that the H-P- curves for different metals in the interval of say 1000 to 3000 kg., from a practical point of view, could be substituted by straight lines, intersecting the absciss axis in a point at the distance  $l = 17,000$  kg. to the left of the origin. As seen by the graph, that fact was likewise borne out in a highly satisfactory way by the determinations now adduced by Mr. O'Neill.



## Iron and Steel Institute.

## ON THE NATURE OF HIGH-SPEED STEEL.

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THIS paper is intended to give a more or less complete account of the physical phenomena occurring in high-speed steel from the time of casting the homogeneous melt to the production of the hardened tools, so far as the changes in the nature, amounts, and distributions of the well-known constituents of such steel are concerned.

It is the intention to emphasise the community of properties of high-speed steel and all other steels—that is to say, high-speed steel, far from being an alloy having wholly unique properties, merely possesses to an unusually marked degree certain of the tendencies which may already be discerned in other steels and alloys. Although the particular combination of elements found in high-speed steel has produced mechanical properties almost un hoped for in any steels, the same metallographic constituents and the same familiar reactions are found in them as in the others.

The authors have found it necessary to avail themselves of the results of many of the methods of investigation applicable to metals. The more recently developed conceptions of crystal structure and hardness constitute the foundation upon which the views offered here have been built, and although much of the evidence is based on microscopic examination, the authors have attempted to interpret the results in such a way as to correlate all the important known properties of high-speed steel.

*The Ingot.*—The ingot of high-speed steel shows the characteristic structure found in all ingots of cast steel. There are columnar grains extending inward, with major axes normal to the ingot surface from which they grew. The central portion of the ingot contains more or less perfectly equi-axed grains. Fig. 2 (Plate XI.) is a photomicrograph of a polished section normal to the surface of a high-speed steel ingot showing clearly the

columnar nature of the large grains which solidify early. Reference to the simplified constitution diagram of Fig. 1 will show the conception of the solidification of high-speed steel which is offered here for consideration. Data to be presented below will show that this simplified diagram must not be considered as accounting for all the phenomena taking place in high-speed steel. The play of the elements and the different behaviours of their carbides will be pointed out in connection with determinations of the compositions of those carbides which are precipitated and (by difference) those which are in solution, under different

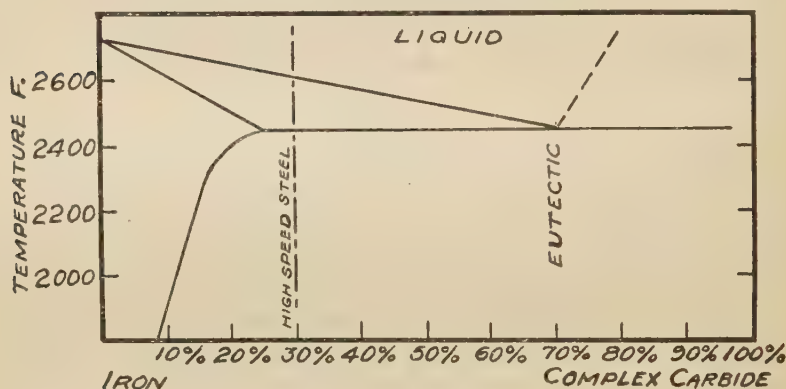


FIG 1.

conditions of heat treatment in the finished high-speed steel. Fig. 1, however, may be considered adequate, and shows at least the probable shape of the solidus curve. For the present the various carbides will be classed indiscriminately together and called carbide. This is in accordance with the belief of the authors that the phenomena of high-speed steel have been obscured by too much attention to chemical phases rather than simplified by due consideration of physical changes and reactions. As, then, the molten high-speed steel solidifies, it forms cored dendrites which never have time for good diffusion and are more or less badly cored, according to the rate of solidification.

Photomicrographs of high-speed steel ingots call to mind the microscopic appearance of white cast iron, and this similarity is sufficiently marked to afford a convenient analogy for use in

study. The high-speed steel structure immediately after solidification is undoubtedly very similar to the structure found in a low carbon hypo-eutectic white iron of about 2.0 per cent. carbon content. Primary grains of austenite, cored and more or less decomposed, plus eutectic (carbide-austenite) regions constitute the fundamental material of the ingot.

The columnar surface grains and the internal grains of the ingot are cored to an unusual degree. The crystallites solidified first differ very greatly from the subsequently filled-in portions of the primary grains. This condition is illustrated in photomicrograph, Fig. 3 (Plate XI.). The magnitude of this disparity in composition of the original austenite grains from centre to periphery, and the persistence of the resulting cored structure, play a most important part in all the subsequent phenomena, and indeed are the cause of most of the manufacturing difficulties encountered. It is well to bear this point in mind constantly, and to recognise at all times that there is a gradation of concentration of carbide from the centres of the dendrites to the eutectic, and that this same gradation persists tenaciously to the finished bar of high-speed steel. It is believed that the diffusion of these carbides, once the steel is solidified, is very slow indeed, and that the ordinary heating and manufacturing operations help comparatively little in securing uniformity.

In the unannealed ingot the usual amount of eutectic found is about 13 per cent. This figure is, of course, slightly in excess of what is normal for the composition, because the metal solidified first is much poorer in carbide elements than the last to solidify, which is completely saturated with them. The last portion of the primary grains to solidify is, as always, richer in all alloying elements. The eutectic temperature is probably very close to 2450° F. (1340° C.). Within the eutectic regions the carbide is the continuous phase, and the austenite fills in the disconnected lakes. For completely homogeneous primary grains the eutectic regions probably would not exceed 10 per cent. of the whole.

The usual ingot of standard practice cools at a rate which not only does not preserve the primary grains wholly austenitic, but even permits of the nearly complete divorce of carbide in a spheroidal condition. In the grains near the surface the structure might be classed as sorbite, while in many of the internal grains

the spheroidisation is coarse. Reference to the photomicrographs will, however, reveal the fact that while in the centre, or first-solidified part of each grain, the carbide agglomeration has taken place to completion—the periphery, or last-solidified portion of each grain, is still austenitic—no carbide has precipitated here. The boundary between these two structures marks the critical composition at which the particular rate of ingot cooling can effect the austenite-pearlite transformation. There can be no inference other than that saturated austenite in high-speed steel is very stable indeed. The stabilising action of alloying elements found in steel is probably in the order carbon, manganese, chromium, nickel, cobalt, molybdenum, and tungsten. In high-speed steel chromium may be the major influence in stabilising the austenite. It will subsequently be seen that in finished steel there is never produced by any heat treatment austenite so rich in the carbide elements as this material in the ingot last to solidify, located near the carbide eutectic regions.

Within the primary grains of the ingot the boundary between the transformed and the untransformed austenite is usually marked by a nearly continuous band of carbide. Just outside this band there is usually present a zone of darkly etching material with a troostitic appearance, representing probably incipient transformation of the retained austenite. The location and appearance of this constituent suggest strongly the development of troostite at a fairly low temperature, whereas the interior of the grains transforms readily enough and at sufficiently high temperature to allow of complete spheroidisation of the carbide. Even this zone probably, to some extent, contributes to the carbide band. This may be caused by the high concentration of carbide elements in the outer region. If diffusion were not so very sluggish in high-speed steel, there would have been a constant migration from these rich regions to the poorer for precipitation. The carbide band within the grain is doubtless the result of such action greatly restricted. It is the authors' opinion that slowness of migration of the alloying elements in high-speed steel is its fundamental property. It will subsequently be seen that in the finished tools there often remains a trace of this composition gradient from centre to edge of each grain.



That there is profound difference between the material of the interior of the grains and the material solidifying later, outside of the carbide dividing-line referred to, may be strikingly seen in Fig. 4 (Plate XI.). To accentuate this difference, specimens from the centre of the unannealed ingots were heated to 1400° F. (760° C.), etched and photographed. The austenite rims of the grains were transformed to the very darkly etching troostite-sorbite material, while the interior region merely became more coarsely spheroidised.

*The Annealed Ingot.*—In manufacturing practice the ingot may be annealed before heating for forging, or it may be taken directly from the casting operation, while still hot, to be forged. In the case of annealing, the cooled ingot is heated up over a period of six to eight hours to a temperature in the neighbourhood of 1600° F. (850° C.), held at this temperature a short time and then cooled slowly, consuming perhaps six to eight hours in cooling to 800° F. (425° C.). Before annealing, the ingot consisted of primary grains (composed of two structures) and eutectic regions. The two structures of the grains were austenite (near grain boundaries and near eutectic regions), and spheroidised pearlite or sorbite. The effect of annealing is readily seen in the photomicrograph (Fig. 5). The whole of the primary grains has changed to spheroidised pearlite and sorbite, and the eutectic patches have been very slightly dissolved. The extent of this solution is clearly shown in Fig. 6. The carbide thus dissolved has been reprecipitated in the cooling time of the anneal, but the composition gradient from centre to last solidifying portion of the grains is still apparent. It should be noted that the ingot now consists of eutectic carbide regions of essentially the same size and formation as when cast, and grains of completely spheroidised pearlite or sorbite. These grains vary from point to point with the original concentration gradient, but there are actually many ferrite grains in which some elements are in true solid solution and within which tiny carbide particles are precipitated. There are two orders of carbide at this stage—the very fine globules and the vastly larger lace-like structures of original eutectic. It is not unusual at this stage to find one of the eutectic areas of a section extending for a sixteenth of an inch, whereas the spheroidised carbide particles are usually not over 0.00004 inch in thickness, although they



are sometimes longer in some dimension, being at times cylindrical or slightly disc-like in contour.

In general, extremely rapid solidification produces very many fine grains in any metal casting, and slower cooling develops large-cored grains. The small grains are most easily homogenised, because although they too are cored, the distances for atomic migration involved in diffusion are short. When, however, extremely slow solidification takes place, a uniform composition is encouraged although the grains are large, because time is given for reaction between melt and solid. The portions of the crystallites freezing first are richer in iron and lower in carbide; given time, they will to a certain extent redissolve, being to that extent replaced in the crystal lattice by atoms in proportions more nearly representative of the melt.

Having in mind this property of solidifying melts, the authors believed that high-speed steel solidified over a long period of time would have a very nearly uniform composition throughout any single primary grain of austenite, and that in such material there would be a smaller amount of eutectic. Such a material was obtained which probably solidified at a rate of not more than  $\frac{1}{2}$  inch in forty-five minutes. The subsequent cooling of this material (after freezing) was somewhat more rapid than would ordinarily occur even in very small ingots, corresponding in rate with an air cooling of rolled bars.

The photomicrographs Figs. 7 and 8 (Plate XI.) show this material as prepared. The photomicrograph Fig. 8 is etched very lightly (so as to disclose no martensite markings), and may be regarded as an ideal microscope view of all high-speed steel as cast at 1340° C. (2450° F.). The other figures show the characteristic martensitic structure as formed unhampered in large grains of austenite. The extreme sluggishness of diffusion (and hence of homogenisation) in solid high-speed steel is clearly indicated here again in the failure of even this method to produce perfectly uniform composition throughout the primary grains. It will be seen that while the original austenite has extensively transformed to martensite in the interior part of every dendrite, martensitisation has stopped near the grain boundaries, and particularly near the patches of carbide. The inference is that the alloying elements were too concentrated to permit the trans-

formation. This unique material was further utilised in several tests recounted below. Its interest lies in the circumstance of its having the highest possible concentration of dissolved carbide elements and the minimum amount of carbide eutectic. The martensite structure, present here so strikingly, will be discussed later in its relation to the usually found structure of hardened high-speed steel.

It may be of interest at this point to show the gradual destruction of the intricate figures of the eutectic regions which accompanies the cogging of the ingot. In general, the original grains of the ingot are deformed in much the same manner as is the whole ingot. Figs. 9 and 10 are photomicrographs of blocks taken from an ingot and deformed to successively greater extents in a single direction, by flattening under the hammer. It will be seen, of course, that the grains are also flattened; but the crumbling of the carbide eutectic is more significant, and shows clearly the origin of the "carbide streaks" in high-speed steel bars. If the large carbide particles in the high-speed ingot were solid integral masses the problem of producing a steel with uniform dissemination of small carbide particles would be difficult indeed, probably requiring high temperatures for solution and extreme severity of reduction. But the carbide regions are frail open structures, and friable as well, hence they disintegrate with comparative ease. In subsequent forging, the carbide eutectic rapidly breaks up so that the distribution of carbide becomes merely a matter of mechanical work to effect a thorough "kneading" of the mass. In the photomicrographs (Figs. 9 and 10, Plates XI. and XII.) only the early stages of the kneading action are shown. A finished bar represents a much more complete breaking up of the carbide regions.

It is perhaps well to point out that the whole of the good effect of prolonged working in rolls or under the hammer is traceable to the uniform distribution of small carbide particles throughout the material. In the utilisation of the steel, provision must have been made for the production of a homogeneous concentrated solid solution, in  $\gamma$ -iron, of as much carbide as possible. This can only be done by the complete crushing up of the original carbide eutectic regions and the obliteration of the original coring effect. The work actually is accomplished well in for instance,

small high-speed steel drill rod, so that the carbide particles derived from eutectic areas are nearly indistinguishable in size from the particles which have been divorced spheroidally from austenite solid solution.

It is not to be inferred that solution and reprecipitation are not responsible for some removal of the carbide streaks of the billets resulting from the eutectic areas. This effect is the more pronounced the smaller the size rolled from the ingot, but in all but the smallest size of steel bars the carbide distribution is largely a matter of mechanical "kneading."

As an example of the persistence of the coring effect of the primary grains attention is called to a photomicrograph (Fig. 11, Plate XII.) of a 1-inch twist drill which was actually an excellent tool. Here is seen a typical carbide streak which is in reality an elongated and crumbled eutectic region. It will be seen, however, that the matrix of sorbitic material about this carbide area is not uniform in composition. Some of the material near the carbide streak is scarcely etched at all, while at more remote points the material etches black. The greater concentration of carbide elements in the adjacent area has probably acted both to reduce the attack of etching acid and also to prevent the precipitation of carbide particles, which, being unresolved, photograph black. Fig. 12 is a photograph of a longitudinal section of a large high-speed steel tool bit. The "streaky" nature of the structure is clearly in evidence, and it will be observed that in the portions etching lighter (the richer regions) the carbide particles remaining from the eutectic are larger than those in the darker region, which were precipitated from solid solution.

To summarise, then, high-speed steel requires generous reduction from the ingot, because, in the large sizes at least, the improvement by homogeneisation is so largely accomplished by mechanical kneading and very slightly by diffusion. The cores are "churned" out gradually and the eutectic regions fragmented. In small sizes, solution during annealing followed by reprecipitation contributes to uniformity of structure and refinement of carbide particles.

*Martensite in High-Speed Steel.*—It will be remembered that the microstructure shown in Fig. 7 (Plate XI.) represents high-speed steel which had solidified with extreme slowness and had then

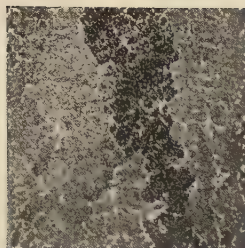


FIG. 2.—Columnar structure of cored grains. Surface of ingot.  $\times 50$ .

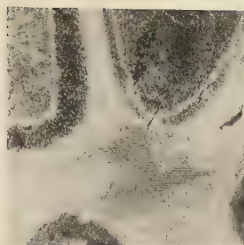


FIG. 3.—Centre of unannealed ingot. Showing contour of eutectic areas and spheroidation of carbide.  $\times 600$ .

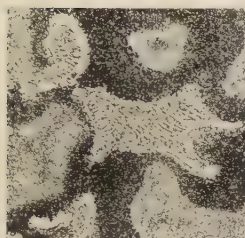


FIG. 4.—Unannealed ingot, drawn at  $1400^{\circ}$  F. ( $760^{\circ}$  C.) for half-hour. Former austenite completely converted to troostite or sorbite.  $\times 600$ .

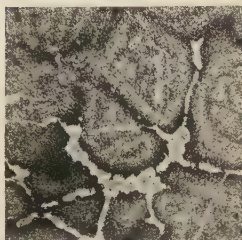


FIG. 5.—Centre of annealed ingot, showing lack of uniformity in composition as a result of coring.  $\times 150$ .

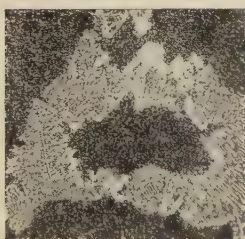


FIG. 6.—Carbide region in annealed ingot showing slight attack by austenite solid solution.

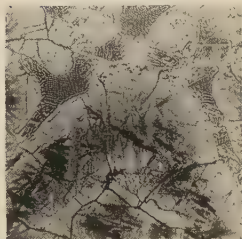


FIG. 7.—Material A, austenite and martensite in original grains.  $\times 600$ .

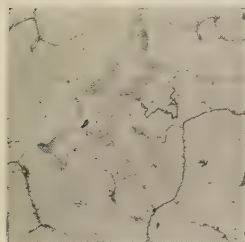


FIG. 8.—Material A, very lightly etched.  $\times 300$ .



FIG. 9.—Annealed ingot, hammered to one-third original height.  $\times 300$ .



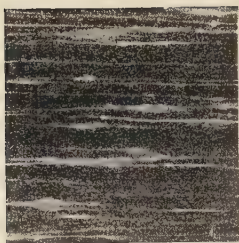


FIG. 10.—Annealed ingot as in Fig. 9, with further deformation. Flattened under hammer to  $\frac{1}{4}$ th original height.  $\times 300$ .

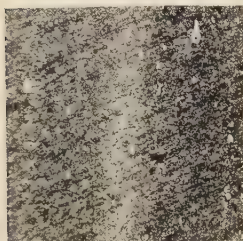


FIG. 12.—Tool bit  $\frac{3}{4}$  in. square with carbide streaks and lack of homogeneity.  $\times 400$ .

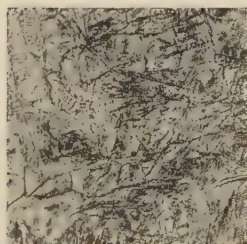


FIG. 14.—Material A, drawn at 1200° F. (650° C.), at max. hardness. Extension of martensite.

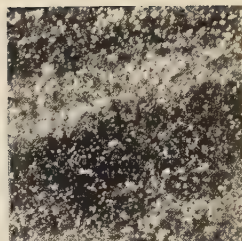


FIG. 11.—Lack of homogeneity in twist drill which showed long service.  $\times 400$ .

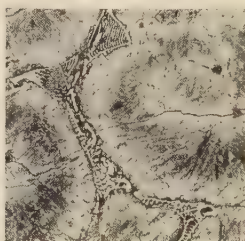


FIG. 13.—Material A, drawn at 1100° F. (595° C.). Martensite and austenite essentially as before drawing.  $\times 600$ .



FIG. 15.—Material A, drawn at 1400° F. (760° C.). Practically complete martensitization—small austenite areas persisting.



FIG. 16.—Material A, drawn at 1500° F. (815° C.). Destruction of martensite beginning.



been cooled rapidly. For the sake of brevity it will here be called material A. It shows large austenite grains with well-defined characteristic martensite markings. In order to determine the stability of this austenite-martensite mixture, and to study the manner of its decomposition, a sample was heated for half an hour at each of a series of comparatively low temperatures, corresponding with drawing temperatures for high-speed steels. The series of photomicrographs (Figs. 13 to 16, Plate XII.) shows the significant manner in which this material responds with the low-temperature reheatings. The lower range of drawing temperatures, up to 900° F. (about 500° C.), has comparatively little effect, the martensite practically not changing at all. The hardness likewise remains about the same, as the original piece showed about 55 Rockwell C,<sup>1</sup> and the value after successive draws at 600° and 900° F. (315° and 482° C.) was still at about the same figure. When, however, the drawing temperature has been raised to 1100° F. (593° C.), it will be observed that the original martensite needles have begun to widen, though still but slightly. The effect becomes much more pronounced at 1200° F. (648° C.). It will also be observed that in the undrawn material the martensite is in evidence in the grains in the central portions only, and that at the high draws the decomposition of the austenite proceeds not only laterally, by a widening of the martensite bands, but also in the direction of the original needles into the austenitic regions in the outer portions of the grains.

It is evident that the mobility of the atoms was not great enough below 1100° F. (593° C.) to permit any significant amount of the preserved austenite to transform into  $\alpha$ -iron. At 1100° F., however, a decisive amount of this austenite does transform, and the change is accompanied by an increase in hardness to about 59 Rockwell C. A further draw at 1200° F. (648° C.) leads to still further decomposition of the austenite, accompanied by further increase in hardness to 64 Rockwell C. The first very marked change in microstructure is observable here. The decomposition

[<sup>1</sup> The dial used in the Rockwell hardness-tester "C" scale records readings made by the impression of a 120° diamond cone at a pressure of 150 kilogrammes. 70 C (the highest reading) corresponds with Brinell hardness No. 745, and 0 C with Brinell No. 140, but the intervening equivalents do not interpolate strictly. For further information as to the Rockwell tester, see paper by S. P. Rockwell, *Transactions of the American Society for Steel Treating*, 1922, vol. ii. pp. 1013-1033.—EDITOR.]

has now progressed sufficiently to establish the fact that the austenite is transforming along regions which are contiguous with the original martensite needles, and that the transformation progresses outward from them in all directions. The transforming process is a slow penetration from the original martensite needles into the austenite regions, the layers of austenite bounding the regions of  $\alpha$ -iron giving way in slow progression as they too transform to  $\alpha$ -iron. Heating further to 1300° F. (705° C.) merely causes the decomposition to proceed further, and at 1400° F. (760° C.) the breaking down is nearly complete. It is significant of the sluggishness of the reactions in high-speed steel, however, that even at a drawing temperature of 1400° F. (760° C.) the austenite formed in material A was not wholly decomposed. The characteristic white patches in Fig. 15 (Plate XII.) show the stable character of this austenitic material, which was still preserved after heating for half an hour at 1400° F. (760° C.).

This photomicrograph (Fig. 15) also gives a very clear and significant indication that high-speed steel probably never martensitises so completely as, for example, a piece of 0.60 per cent. carbon steel. The number of martensite needles in high-speed steel is limited, and the intervening regions are austenitic. Obviously, this is an instance where the fallacy of assuming that a specimen showing martensite needles is completely martensitic must be avoided.

It is believed that the phenomena observed in this material A are perfectly characteristic of the reactions taking place in the drawing of a piece of quenched high-speed steel. The authors believe that this specimen, far from being extraordinary, merely possesses to a more obvious and demonstrable degree the structures found always in high-speed steel. In newly quenched high-speed steel the austenite grains have numerous martensite markings, which can be observed after suitable etching but which are not so clear as in the present instance, because the austenite grains are not so homogeneous, and are often small and thoroughly strewn with carbide particles. This lack of homogeneity in ordinary quenched high-speed steel is due to two factors: (1) the coring in the original dendrites has led to the presence of composition gradients which have not been wholly removed; (2) the accidental placing of eutectic carbide particles at

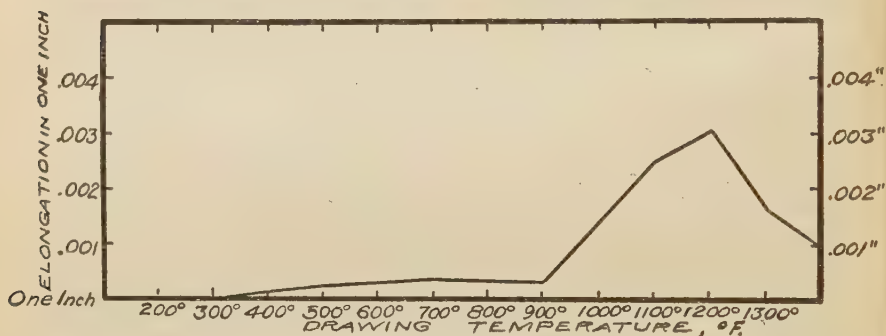
numerous scattered points, due to the working of the steel and the resultant kneading and churning action, has caused small regions of local concentration gradients (due to solution) when the steel was heated to the quenching temperature. In material A the austenite grains formed with good diffusion in solidification, so that they are quite homogeneous, and the eutectic carbide is of course segregated in grain boundaries. In other words, the crystallisation in the austenite lattice in material A has been much more symmetrical and uniform throughout large regions, so that the recrystallisation to  $\alpha$ -iron (martensite needles) in the quench could take place without interruption along much longer paths and more completely.

The hardness changes which accompany this gradual breaking down of the austenite are of interest in connection with the secondary hardness phenomena in high-speed steel. Material A, when reheated to low temperatures, preserved its original hardness of 55 Rockwell C, unchanged up to a temperature of 900° F. (482° C.). At 1100° F. (593° C.) there was sufficient recrystallisation into fine-grained  $\alpha$ -iron to raise the hardness to 59, and at 1200° F. (648° C.) the proportions of austenite and transformed material were such as to increase the hardness still further to 64 Rockwell C. Above this temperature the further transformation of austenite was more than balanced by grain growth and carbide formation in the regions transformed previously.

This is shown by the fact that the specimen drawn at 1300° F. (705° C.) showed a drop in Rockwell hardness to about 58, and the subsequent draw at 1400° F. (760° C.) lowered the hardness still further to about 49. It must be remembered that this softening does not indicate complete softening throughout the piece—it is merely a preponderance of the effect of the portions that are softening over the austenite which hardens (changes to  $\alpha$ -iron) at these temperatures.

These same changes in material A can be followed by observing the changes in volume which occur on reheating. A test-piece 2.0 inches long was prepared, and ground as nearly as possible with parallel ends, so as to make it possible to measure the length after various heat treatments. The length was measured on two instruments. One was equipped with an Ames dial reading to 0.001 inch with a 1:10 multiplying device, so that the

instrument could be read directly to 0.0001 inch. The other was a Federal dial reading directly to 0.0001 inch. The readings given are in each case the average from the figures of two operators on each of the two instruments. It is to be observed that there is no significant change in the length (*i.e.* in the volume) until the steel has been reheated to 1100° F. (593° C.). At this temperature a very considerable expansion sets in, to be followed by further expansion at 1200° F. (648° C.). Beyond this temperature the steel begins to contract, but here again it must be borne in mind that we observe merely a preponderance of effect. The contraction due to formation of carbides and to grain growth of the sub-microscopic grains of  $\alpha$ -iron is more than sufficient to counter-



[Fig. 17.]

balance the expansion due to transformation of further austenite. Comparison of the graphs of expansion and hardness, Figs. 17 and 18, shows their similarity at once.

*Carbides in High-Speed Steel.*—It seemed desirable to secure some data as to the extent to which the various chemical elements in high-speed steel enter into the reactions involved in heat treatment. It was believed that if a piece of high-speed steel were quenched at a high temperature and then dissolved in a suitable chemical reagent, the alloying elements which had dissolved in the  $\gamma$ -iron or had remained in  $\alpha$ -iron would go into solution in the liquid, while any residual carbides found would represent carbides still undissolved in the  $\gamma$ -iron phase after the heating of the steel for quenching. In the same way, the re-formation of carbides on drawing would ultimately lead to the formation of granules of such size as to resist chemical attack.



It is obvious that there is no justification for believing that the electro-chemical actions correspond quantitatively with the states of solution and precipitation of carbides in the steel. Indeed, it is altogether probable that, in the case of at least some of the carbides, the reagent can attack and decompose them the more readily as the size of the crystal aggregate becomes smaller and approaches molecular proportions. However, it is believed that the data presented give a good indication of the changes on going into solution as the quenching temperature is raised, and it may be assumed with safety that the general trend at least is as indicated for the drawing temperatures.

An electrolytic method for solution of the heat-treated speci-

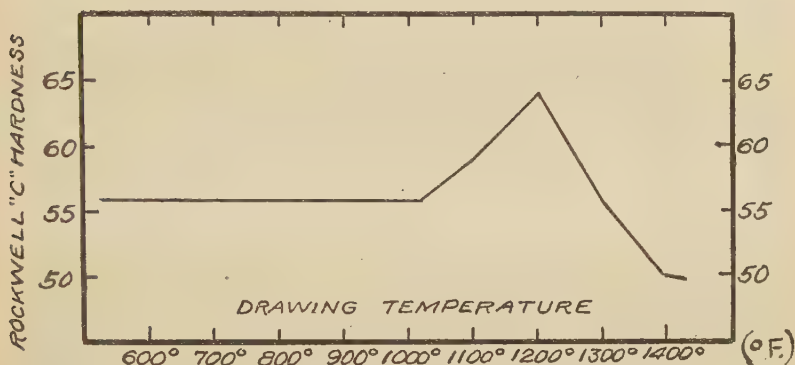


FIG. 18.

mens proved to be very convenient. The specimen was made the anode in a small electrolytic cell of about 1 litre capacity, using an electrolyte of 1:10 hydrochloric acid, and a copper cathode. A weighed specimen was electrolysed with a current of about 0.3 ampere for about 100 hours, changing the electrolyte at intervals of about 24 hours. Upon completion of the attack the still undissolved stub was weighed, giving by difference the weight of steel destroyed. The "carbide residue" was filtered in an alundum crucible, dried and weighed. Although this did not represent the weight of true carbide residue from the steel (due to an intervening fact to be discussed later), the true carbide was easily estimated by a further procedure.



The steel selected for this series of tests had the following composition :

	Per Cent.
Carbon . . . . .	0.70
Tungsten . . . . .	18.50
Chromium . . . . .	4.17
Vanadium . . . . .	1.11

The steel, in the form of commercial annealed  $\frac{3}{8}$  inch square bars, was cut into pieces about 4 inches long. A series of these pieces was hardened after the usual manner of high-speed tools. They were quenched from a gas-fired furnace into oil; the reheating at the low temperatures was done in oil, and at the higher temperatures in an electric "oven."

A group was heated at each of the following temperatures—1700°, 1900°, 2000°, 2100°, 2200°, 2300°, 2350°, 2400° F. (926°, 1038°, 1093°, 1150°, 1205°, 1260°, 1288°, 1310° C.)—and quenched in oil. From each group one specimen was kept as quenched, and one was reheated to each of the following drawing temperatures—300°, 500°, 700°, 900°, 1100°, 1200°, 1300° F. (150°, 260°, 390°, 482°, 593°, 648°, 705° C.). There were thus sixty-four specimens in all. As a matter of incidental interest the specimens, after heat treatment, were tested for Rockwell hardness, with the results shown in the chart of Fig. 19.

The specimens were then subjected to the above electrolytic solution process. It was observed early that the specimens which had been quenched at the highest temperatures and had not been drawn showed a very considerable precipitate of tungstic oxide in the electrolytic cell, along with the true carbide residue. This appeared to have the possible significant interpretation that the tungsten carbide, when dissolved in the iron, went into solution atomically and not as a compound. It can of course be argued that tungsten carbide, if in solution in iron molecularly, would be subject to the same attack because of the extreme minuteness of the crystal aggregate. However, the phenomenon is considered worthy of attention, especially because the amount of tungstic acid varies in close conformity with the heat treatment.

The carbides were analysed for total carbon, tungsten, chromium, and vanadium. Portions were also treated with ammonia and filtered, in order to determine in the filtrate the amount of tungstic oxide present with the carbide, as explained above.

From these analytical data, and from the weights of carbide found undissolved, it was possible to compute the amounts of the elements which had been dissolved in the steel on quenching, and to discover the trend of their precipitation on drawing.

Analyses of the carbide in annealed steel gave the following probable average :

	Per Cent.
Carbon . . . . .	2.3
Chromium . . . . .	6.3
Tungsten . . . . .	61.0
Vanadium . . . . .	3.6
Iron (by difference) . . . . .	26.8

The amount of the carbide and its composition indicate that

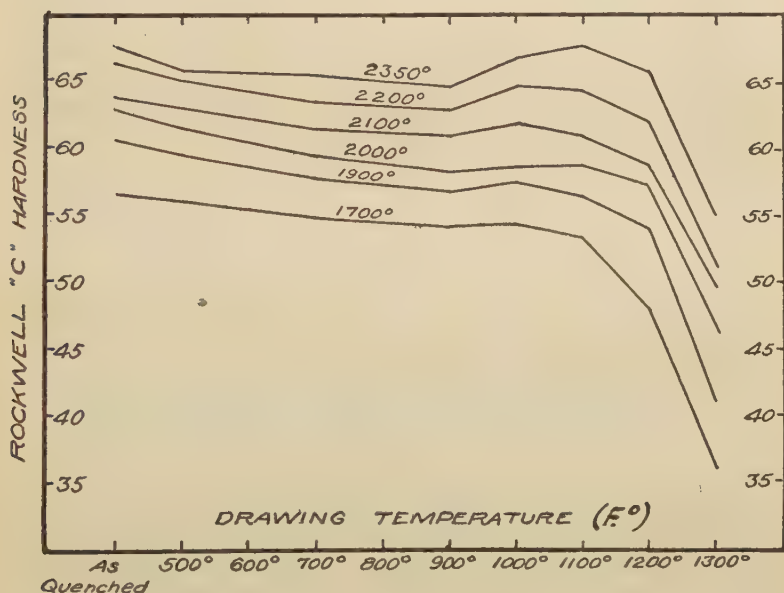


FIG. 19.

approximately all of the carbon, all of the tungsten, and all of the vanadium are in the form of carbide in the annealed steel; but it is interesting to note that only about half of the total chromium is in the carbide. Annealed high-speed steel, then, may be considered to consist of about 70 per cent. (by weight) solid solution of chromium in  $\alpha$ -iron, and 30 per cent. complex carbide.

Of the maximum 30 per cent. carbide content, the most dissolved in any quench was about 13 per cent. Judging from the appearance of material A, it is conceivable that by heating the steel for a long time just below incipient fusion to secure rather complete diffusion of the carbide, it would be possible to dissolve about 20 per cent. carbide, leaving about 10 per cent. residual. The presence of eutectic in material A, which was solidified with such extreme slowness, precludes the probability that the carbide would be dissolved by any treatment.

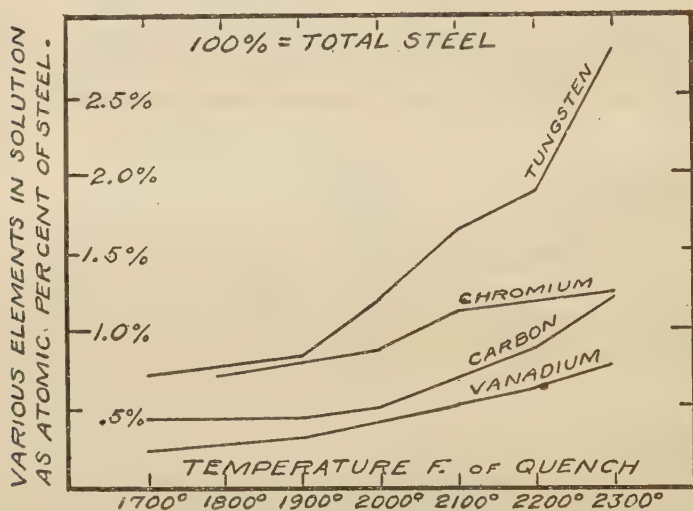


FIG. 20.

The amounts of the various elements dissolved at successively higher quenching temperatures are shown in Fig. 20, plotted in atomic percentages. It is evident that the solubility of the elements increases rather rapidly as the steel is heated in the higher ranges of temperature. This fact has also been incorporated in the carbide solubility line of the equilibrium diagram (Fig. 1). The total amount of carbide remaining undissolved after quenching at successively higher temperatures is shown in Fig. 21.

On drawing these quenched specimens the precipitation and re-formation of carbides lead to a gradual increase in the amount of "residual carbide." This decrease in the amount of dissolved element, as the drawing temperature is raised, is

shown in Fig. 22 for tungsten. This diagram shows also the relative amounts in solution after various quenching temperatures, and may be taken as representative of the way in which the various elements go into solution and are reprecipitated. It must always be remembered in this connection that the analyses, after drawing, cannot be considered to represent accurately the amount of precipitated carbide, because the freshly formed carbide would in many cases be in such a fine state of

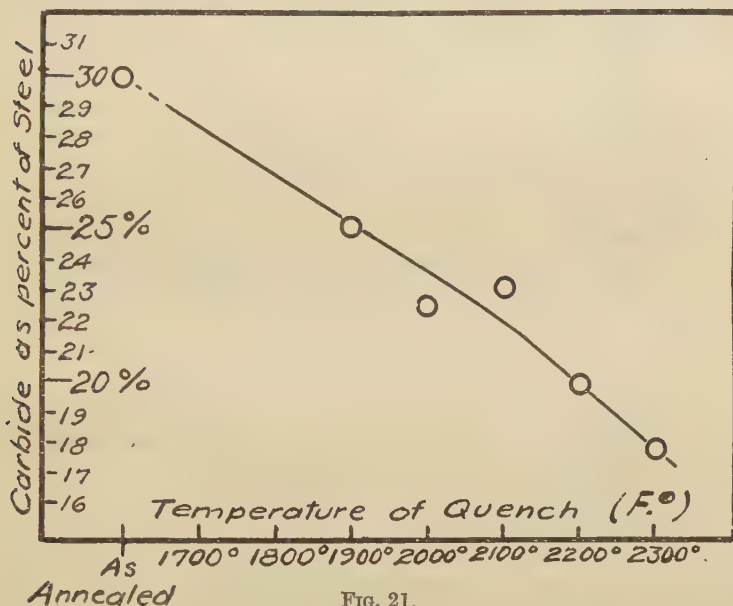


FIG. 21.

aggregation as to be susceptible to electro-chemical attack, and even though unattacked would be of colloidal size and pass through the filter.

The relative amounts of the various elements in solution can best be shown by plotting the results as atomic percentages, for the obvious reason that this corresponds with the relative number of foreign atoms in the austenite lattice. The atomic percentages of the elements carbon, tungsten, chromium, and vanadium in solution, after quenching from 2300° F. (1260° C.), and followed by various draws, are shown in Fig. 23. Perhaps the most striking fact observed here is the relatively large

amount of chromium in solution as compared with all the other elements. This follows not only from the lower atomic weight

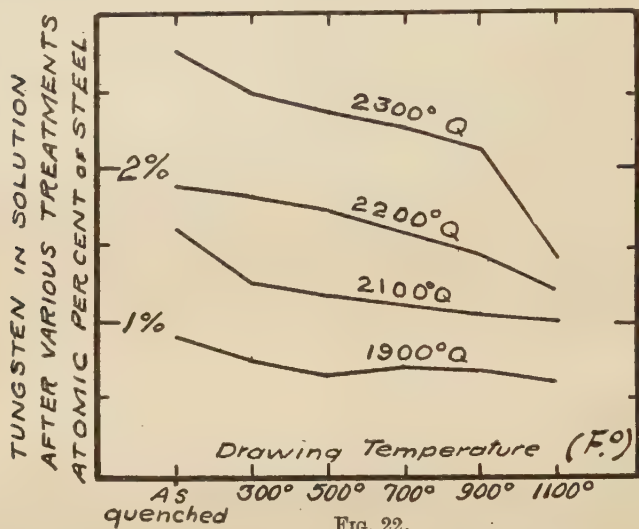


FIG. 22.

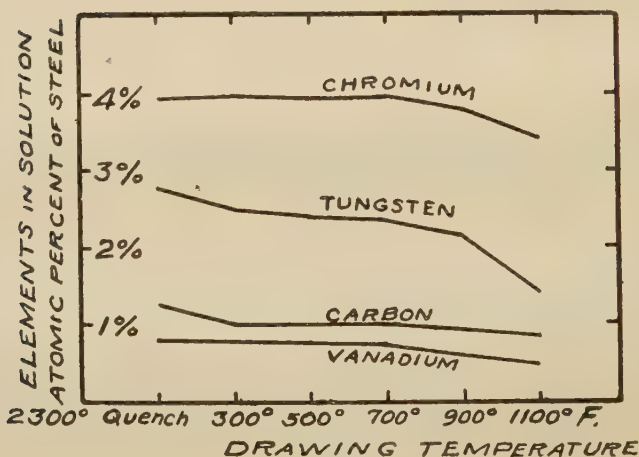


FIG. 23.

of chromium as compared with tungsten, but also from the fact that half the total chromium is already in solid solution in the annealed state. Unlike carbon, chromium is soluble in  $\alpha$ -iron to a great extent.



Approximately the same relation among the elements is observed at all the different quenches, although, of course, the absolute amounts vary greatly. An approximate conception of the curves at the other quenching temperatures can be derived by imagining the various graphs to be displaced vertically, according to the variations in solubility shown in Fig. 20.

Table I. gives both in atomic percentages and in weight percentages the amounts of the elements in solution after successively higher quenches. Table II. gives in similar units the amounts in solution after quenching at 2300° F. (1260° C.) and subsequently drawing at the temperatures stated.

TABLE I.—*Percentages of Tungsten in Solution after Various Heat Treatments.*

Drawing Temperature.		No Draw.	300° F. (150° C.)	500° F. (260° C.)	700° F. (390° C.)	900° F. (482° C.)	1100° F. (593° C.)
Quenching Temperature.							
1900° F. (1038° C.)	Weight per cent.	2.74	2.24	1.95	2.20	2.20	1.75
	Atom „	0.92	0.76	0.66	0.74	0.74	0.59
2100° F. (1148° C.)	Weight per cent.	4.75	3.75	3.50	2.70	3.18	2.95
	Atom „	1.60	1.26	1.18	0.91	1.07	0.99
2200° F. (1205° C.)	Weight per cent.	5.58	5.45	5.32	3.55	4.30	3.56
	Atom „	1.88	1.84	1.79	1.20	1.45	1.20
2300° F. (1260° C.)	Weight per cent.	8.20	7.33	7.02	6.88	6.28	4.20
	Atom „	2.77	2.48	2.37	2.32	2.12	1.41

TABLE II.—*Percentages of the Elements in Solution after Quenching from 2300° F. (1260° C.) and then Drawing at Various Temperatures.*

Drawing Temperature.		No Draw.	300° F. (150° C.)	500° F. (260° C.)	700° F. (390° C.)	900° F. (482° C.)	1100° F. (593° C.)
Alloying Element.							
Carbon	Weight per cent.	0.24	0.19	0.11	0.19	0.18	0.16
	Atom „	1.24	0.98	0.57	0.98	0.93	0.82
Chromium	Weight per cent.	3.31	3.35	3.30	3.33	3.18	2.85
	Atom „	3.95	4.00	3.94	3.97	3.79	3.40
Tungsten	Weight per cent.	8.20	7.33	7.02	6.88	6.28	4.20
	Atom „	2.77	2.48	2.37	2.32	2.12	1.41
Vanadium	Weight per cent.	0.62	0.61	0.60	0.58	0.46	0.35
	Atom „	0.76	0.74	0.73	0.71	0.56	0.43

## THE HARDENING OF HIGH-SPEED STEEL.

It would seem desirable, finally, to consider the mechanism of the hardening of a piece of finished high-speed steel.

High-speed steel, as has been seen, may be considered, for a first approximation, essentially a binary alloy, of which one constituent is a solid solution of chromium in iron, and the other the complex carbide of high-speed steel. The finished bar contains on an average 30 per cent. carbide, but this carbide is not evenly distributed. A little more than half of it is in the form of fine particles which have been precipitated from solid solution after the material solidified. Due to coring in the original dendrites, which has not been completely removed, there is a concentration-gradient from the centres to the edges of these areas which represent the original grains. The remainder of the carbide is in comparatively coarse particles, which represent the plates of carbide in the original eutectic. These are still present in fairly pronounced streaks throughout the piece. Consider this steel aggregate to be heated now to the usual quenching temperature for high-speed steel. The solubility of the carbide in the  $\gamma$ -iron increases rapidly as the temperature rises, so that at the highest temperature nearly half of the total carbide can be dissolved in the matrix. But owing to the immobility (the sluggishness of diffusion) of the alloying elements, especially the tungsten, there is formed an austenite whose homogeneity can never be much better than that of the annealed steel from which it formed. In addition, the fortuitous placing of the larger carbide particles from the original eutectic causes small regional concentration gradients which interfere further with the homogeneity of the austenite.

It is to be observed here that the particles of excess carbide exercise a very useful function in preventing grain growth at this high temperature. But for the obstructing action of these sluggish particles of excess carbide, grain growth at the high temperatures used for high-speed steel would be so rapid as to render the steel useless because of brittleness.

Having been heated suitably at the high temperature, the steel is now quenched. In this quenching process a portion of the austenite is transformed to martensite, so that freshly

quenched high-speed steel shows under the microscope grains consisting of a mixture of austenite and martensite, and distributed through them the excess carbide particles that were not dissolved. A light etching reveals only the austenite grains and the excess carbide particles, but suitable further etching shows the martensite to be present very definitely. The relative proportions of martensite and preserved austenite undoubtedly vary from place to place, following the variations in concentration of the carbide. The regions lower in carbide would contain more martensite, and those richer in carbide more austenite. A piece of freshly quenched high-speed steel is thus to be conceived as containing regions of austenite-martensite mixtures of widely varying stability. Perhaps over half of the steel, other than carbide, is austenitic after the quench.

These differences in stability also become noticeable on drawing the quenched steel. We have seen that a saturated austenite shows great stability on drawing, as evidenced both by the retention of hardness and by the lack of change in volume. But the austenite in ordinary quenched high-speed steel is not all saturated, and there are many regions where the concentration of carbide is much less than the saturation value. It is probably in these regions of lower concentration that the softening takes place which is observed in high-speed steel on drawing at low temperatures. These regions are predominantly martensitic, and on drawing at low temperatures the martensite decomposes and softens. Such low alloy martensite resembles carbon steel martensite. The decomposition of this martensite can be traced both in the hardness and in the shrinkage, for we have seen that saturated austenite (material A), having very little martensite, retained both its hardness and its original volume on reheating as high as 900° F. (482° C.), whereas ordinary high-speed steel both softens and shrinks on being drawn in this lower range of temperature.

When the steel is now drawn at about 1100° F. (593° C.) the phenomenon of secondary hardness is observed. The austenite regions are transformed, at least to a considerable extent, to martensite or troostite. The reaction takes place in all regions throughout the piece, although those with a lesser proportion of austenite (lower concentration of carbide)

transform a little more readily and therefore at a slightly lower temperature than do the richer areas. The total effective hardening at 1100° F. (593° C.) may be considered as representing the "algebraical sum" of the hardening effect of the transformation of the varied austenite and the softening of the various martensites.

It is well to emphasise at this point that the phenomenon of secondary hardness is by no means restricted to high-speed steel; and it is necessary to distinguish between secondary hardness and red-hardness. The retention of austenite on quenching is characteristic of many alloy steels on heating to sufficiently high temperatures. When such an austenite is reheated to low temperatures secondary hardening sets in, owing to the formation of sub-microscopic grains of  $\alpha$ -iron and the precipitation of fine carbide particles. It is likely that if the tungsten in high-speed steel were omitted altogether the remaining elements alone would suffice to cause the retention of austenite and the appearance of secondary hardening.

The usefulness of high-speed steel is due, however, to the extent to which it exhibits the property of red-hardness, and it is here that tungsten plays its rôle. The large, heavy, immobile atoms of tungsten act by supporting the structure at these slightly elevated temperatures. Obviously, if the carbide elements—particularly tungsten—can migrate through the martensite to form large spheroids of carbide, then the source of hardness is lost. In steels with low alloy content this diffusion does occur, but the conclusion may be drawn that the tungsten atom is still too immobile even at a dull red temperature to diffuse through the distorted  $\alpha$ -iron lattice so as to form the large carbide particles characteristic of annealed steel.

### SUMMARY.

Examination of ingots of high-speed steel and of pieces of steel made from them, but specially treated mechanically and thermally, has been found to account for numerous phenomena, and to afford striking examples of the many structures found in normal high-speed steel.

A material solidified with special slowness so as to secure



good diffusion was found to exhibit in marked degree certain martensite and austenite phenomena, which are presumably characteristic of all high-speed steel, although difficult of recognition.

An electro-chemical solution method was employed to determine the reactions exhibited by the various chemical elements, when high-speed steel is heat-treated at various temperatures.

Hardness and expansion measurements further elucidated the investigation of the reactions taking place during heat treatment.

### CONCLUSIONS.

1. High-speed steel solidifies very much after the manner of a 2 per cent. carbon white cast iron, in which cementite is replaced by a complex carbide. It is outstandingly hyper-eutectoid.

2. The coring of the original dendrites, and the concentration of carbide at the eutectic regions, contribute to a lack of desirable homogeneity, which is then obtained only with the utmost difficulty, and rarely with completeness.

3. The original eutectic areas, which form the familiar carbide envelopes, break down readily, owing to their weak structure. Although these carbides are never present in very large solid grains, their original close association in islands makes thorough redistribution in the subsequent working difficult.

4. The martensite present in ordinary newly quenched high-speed steel is more difficult to recognise because small concentration gradients disturb the homogeneity of the original austenite grains. These concentration gradients are due to the coring of the original dendrites, and to the accidental placing of eutectic carbide particles throughout the mass.

5. The austenite formed in quenching high-speed steel, far from being decomposed completely on reheating at 1100° F. (593° C.), may to some slight extent persist even past 1400° F. (760° C.).

6. High-speed steel contains about 30 per cent. by weight of complex carbide. In the annealed steel, approximately all the carbon, tungsten, and vanadium is found in the "carbide," together with about half of the chromium. Except in drill



rods of high-speed steel there are distinctly two sizes of carbide particles, the fragments of the eutectic and the reprecipitated globules.

7. Under average hardening conditions somewhat less than half of this carbide is dissolved in the matrix on heating for quenching. Heating for a long time so as to approximate equilibrium conditions might possibly cause as much as two-thirds of the carbide to go into solution.

8. The solution of the carbides on heating begins at comparatively low temperatures, and continues in a manner that would correspond with a modified  $A_{cm}$  line.

9. Hardening of high-speed steel is brought about by dissolving as much of the carbide-forming elements as possible in  $\gamma$ -iron, and then reheating to form the hardest possible combination of martensite and sub-microscopic carbide particles. The high temperature required for producing the rich austenite is not disastrous to grain size, due to the obstruction offered by the residual carbide. The hardness is persistent at high temperatures as a result of the outstanding property of the alloy—the low rate of diffusion of the carbide elements.

## CORRESPONDENCE.

Colonel N. T. BELAIEW (London) wrote to congratulate the authors on the very interesting experimental evidence brought forward to show the nature of high-speed steel. He was particularly interested in that part of the work which tended to show the close similarity of the structure and of some of the properties of the steels investigated by the authors, and that of hypereutectoid high-carbon steels.

On p. 249 the authors stated that "high-speed steel, far from being an alloy having wholly unique properties, merely possesses to an unusually marked degree certain of the tendencies which may already be discerned in other steels and alloys." He (Colonel Belaiew) was interested in such statements and in like evidence, as he considered that the study of the properties of high-speed steels would be considerably benefited by comparison with high-carbon steel, and more especially with damascene steel. Since 1906, when he started his first studies under the guidance of Professor Tschernoff, he had been impressed by the idea that the damascene steels and, generally speaking, the "damascene process," if attentively studied and properly understood, would lead, in the first instance, to improvement in the quality of high-carbon steels, and, next, to a better understanding of the nature of high-speed steels. A paper to that effect, with special reference to high-speed steels, was read by him in 1911 before the Russian Metallurgical Society, and in 1918 and 1921 before the Iron and Steel Institute. The problem was dealt with at some length in the latter paper, and the comparison of that paper with the authors' paper would show the complete agreement between the views of the authors and the writer on the main issues of the problem.

There were, however, some details which seemed to be of sufficient importance to be mentioned. For instance, he (Colonel Belaiew) would like to endorse the authors' remarks that the "gradation of concentration of carbide from the centres of the dendrites to the eutectic persists tenaciously in the finished bar . . ." (p. 251). He would like to emphasise that statement and to recall that, according to his views, such persistence in carbide distribution led in the damascene articles to their beautiful macrostructure, revealed as watering. The accompanying photogram (Fig. A.) of a sword in the Wallace collection, reproduced with the kind permission of the Trustees,<sup>1</sup> showed the persistence of the structure and the distribution of the veins of the carbides. He wished that figure to be compared with the authors' Figs. 9 and 10; in spite of the difference in scale, the analogy would be clearly seen.

The uniform distribution of carbide particles under hammer or rolls, referred to by the authors on p. 255, was also one of the features

<sup>1</sup> "Crystallisation of Metals," by Colonel N. T. Belaiew. London. 1923.  
1924—ii.

of damascene structures and, moreover, was, in his (Colonel Belaiew's) opinion, responsible for the gradual increase of ductility of very high carbon steels and semi-steels during forging. He was also very interested in the paragraph on hardening, as he considered that the

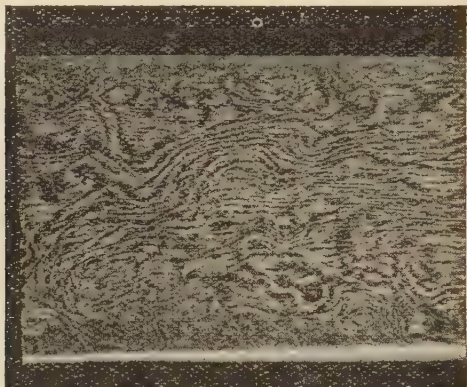


FIG. A.—Damascene Blade from the Wallace Collection.  $\times 1$ .

carbide particles exercised a considerable influence on the hardness of the finished article, partly, as shown by the authors (p. 268), in preventing grain-growth, but also by possible key-acting, and even as embedded hard particles.

## Iron and Steel Institute.

THE CHANGES OF VOLUME OF STEELS  
DURING HEAT TREATMENT.

By LESLIE AITCHISON, D.MET., B.Sc., F.I.C. (BIRMINGHAM),

AND

GEORGE REGINALD WOODVINE (SHREWSBURY).

In September 1922 the authors presented a number of test results dealing with the dilatation and contraction of air-hardening nickel-chromium steels during various and peculiar heat treatments. The present record deals with an extension of the series of tests previously recorded, primarily intended to investigate more particularly two points that had emerged during the initial series of experiments. The first of the matters that appeared to require careful consideration was whether the lateral expansion and contraction of the metal is equal to the longitudinal—*i.e.* whether the steel expands and contracts as a truly isotropic material, or whether, as has been suggested, its behaviour in the two directions of the grain is different. The second point to call for further investigation follows from the fact that the results previously recorded were obtained upon specimens that had cooled in the dilatometer from the hardening temperature, and had therefore cooled at a fairly slow rate. In consequence, the specimens were in general not fully hardened, and therefore not really in a condition that could be accurately described as “air-hardened.” It seemed important, therefore, to examine whether this method of cooling produced any difference in the subsequent dilatometric behaviour of the steel as compared with the same steel fully hardened.

The first of these points has been investigated by examining two forms of material from the same cast. The previous experiments had all been carried out on round bars. From the same cast of steel flat bars of a section  $2\frac{1}{4}$  inches by  $\frac{7}{8}$  inch were rolled. From these flat bars test-pieces of the same dimensions as used previously were cut in two directions—*i.e.* parallel to and perpendicular to the length of the bar. These pairs of specimens

were treated and tested in similar ways, whilst a longitudinal specimen from the round bar previously used was also subjected to the same treatment.

The dilatometric behaviour of the fully hardened steel has been examined in two ways. In the first set of tests the specimens were heated in a separate furnace to the specified temperature, and then removed and hardened in the still air. They were then trued up very lightly and carefully, and examined during various treatments in the dilatometer. In the second method the specimens were hardened whilst in the dilatometer by cooling at a much more rapid rate than that formerly employed. This increased speed of cooling was brought about by passing a stream of compressed air through the tube of the dilatometer until the temperature of the specimen had fallen to that of the atmosphere. In order to avoid the oxidation of the specimens by the compressed air, they were copper-plated before being put into the instrument. The layer of copper on the sides of the specimens combined with the protective effect of the silica discs at the two ends of the specimens prevented any oxidation of the surfaces and made the dilatometer records therefore quite reliable. Specimens prepared in these two ways were therefore suitable for submission to the repeated tempering experiments that had been executed on the steels cooled slowly in the dilatometer, which formed the subject-matter of the former report.

All the experiments were carried out in the dilatometer previously described. The steel used had the analysis already reported, a considerable proportion of the experiments being made on specimens cut from the bars previously employed, whilst the flat bars were rolled from the same cast of steel. Unless it is otherwise recorded, the rates of heating and cooling in the present series of experiments were the same as those previously reported. In all respects, in fact, the second and first series of tests were made under similar conditions, except where a difference is specifically notified.

The actual experiments carried out to ascertain whether the longitudinal and lateral expansions of the steel were similar are described below. No such extensive tests as had been made originally appeared to be required in order to examine this point, and the tempering treatments were therefore only carried out at



two temperatures—200° C. and 600° C. The specimens employed and the treatments given comprised the following :

- A.F.L.—Longitudinal specimen from the flat bar, heated in a separate furnace to 830° C., hardened in air, then tempered in the dilatometer repeatedly at 200° C. till no further change of length occurred. Five successive heatings were required (see Fig. 1).
- A.F.T.—Lateral specimen from the flat bar treated in the same way as A.F.L. Five successive temperings were required to produce a constant length (see Fig. 1).
- A.R.L.—Longitudinal specimen from the round bar treated in the same manner as A.F.L. Three successive temperings were required to produce a constant length (see Fig. 3).
- B.F.L.—Longitudinal specimen from the flat bar hardened like A.F.L. but tempered in the dilatometer repeatedly at 600° C. till no further change of length occurred. Four successive heatings were required (see Fig. 2).
- B.F.T.—Lateral specimen from the flat bar treated in the same way as B.F.L. Four successive temperings were required to produce a constant length (see Fig. 2).
- B.R.L.—Longitudinal specimen from the round bar treated in the same manner as B.F.L. Four successive temperings were required to produce a constant length (see Fig. 3).

A comparison of the behaviour of the three specimens tempered at 200° C., or the set tempered at 600° C., as shown in Figs. 1, 2, and 3, reveals the fact that there is no noticeable difference in the

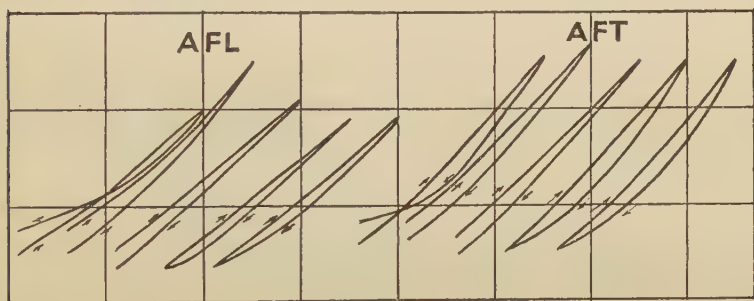


FIG. 1.

behaviour of the longitudinal and transverse specimens. The contraction of the different kinds of specimens is quite similar, and it would be difficult, if not impossible, to pick out any noticeable variation in the habits of either type of test-piece. From these experiments (which have been confirmed by numerous others made during the course of the work) it may be concluded with safety that the rolled steel behaves isotropically, and that there is no appreciable directional effect in its expansion and

contraction. From this result it follows that the experiments described both here and previously may be taken accurately



FIG. 2.

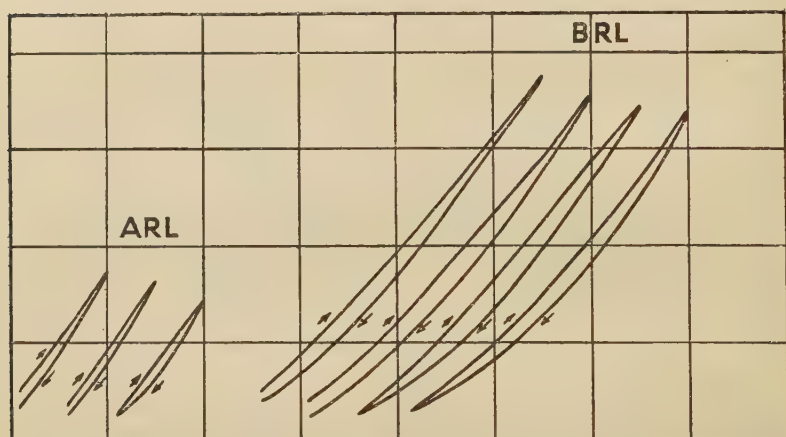


FIG. 3.

to represent changes of volume, although the changes actually observed are only those of length.

An extensive series of experiments have been carried out to provide the material for a comparison of the behaviour during tempering of the specimens cooled slowly in the dilatometer and

those hardened in the air outside the instrument, and therefore cooled at the normal "air-hardening" rate. The specimens chosen for these tests were all taken from the round bar employed for the first set of experiments. In every experiment the specimens were machined to size, plus a grinding allowance, and then were hardened in the air. They were afterwards carefully ground on the ends and cleaned on the sides before being put into the dilatometer for testing. The hardening of all the specimens was carried out similarly and simultaneously, and the temperature employed was  $830^{\circ}\text{C}$ . A complete series of temperings was made at each of the following temperatures— $100^{\circ}$ ,  $200^{\circ}$ ,  $300^{\circ}$ ,  $400^{\circ}$ ,  $500^{\circ}$ ,  $600^{\circ}$ ,  $700^{\circ}$ , and  $750^{\circ}\text{C}$ . The method of testing was the same as for the first series of treatments, the specimens being tempered by successive cycles of heating and cooling to the selected temperature until there was no further change in length. The specimens were not maintained at the tempering heat at all, but as soon as they had attained the specified temperature were allowed to cool again to the atmospheric temperature and then reheated if necessary.

The results of the treatment given at the different temperatures are as follows :

- C.L.10.—Tempered at  $100^{\circ}\text{C}$ ., achieved constant length after four reheatings, the final length showing a contraction of 3 scale divisions from the hardened state.
- C.L.20.—Tempered at  $200^{\circ}\text{C}$ ., the length became constant after three reheatings, the final length showing a contraction of 10 scale divisions from the hardened state.
- C.L.30.—Tempered at  $300^{\circ}\text{C}$ ., the length became constant after four reheatings, showing a final contraction of 14 scale divisions.
- C.L.40.—Tempered at  $400^{\circ}\text{C}$ ., the length became constant after three reheatings, the final length showing a contraction of 10 scale divisions.
- C.L.50.—Tempered at  $500^{\circ}\text{C}$ ., the length became constant after three reheatings, the final length showing a contraction of 20 scale divisions.
- C.L.60.—Tempered at  $600^{\circ}\text{C}$ ., the length became constant after four reheatings, the final length showing a contraction of 10 scale divisions.
- C.L.70.—Tempered at  $700^{\circ}\text{C}$ ., the length became constant after three reheatings, the final length showing a contraction of 5 scale divisions.
- C.L.75.—Tempered at  $750^{\circ}\text{C}$ ., the length became constant after three reheatings, the final length showing a contraction of 2 scale divisions.

The first heating and cooling curves of the above specimens to their respective temperatures are shown in Fig. 4, and these can be compared with the curves in Fig. 3 of the previous paper. In Fig. 5 is shown the volume at atmospheric temperature of the various specimens after once tempering at the different

temperatures plotted against the tempering temperature. This curve can be compared with the corresponding curve shown in Fig. 4 of the previous paper.

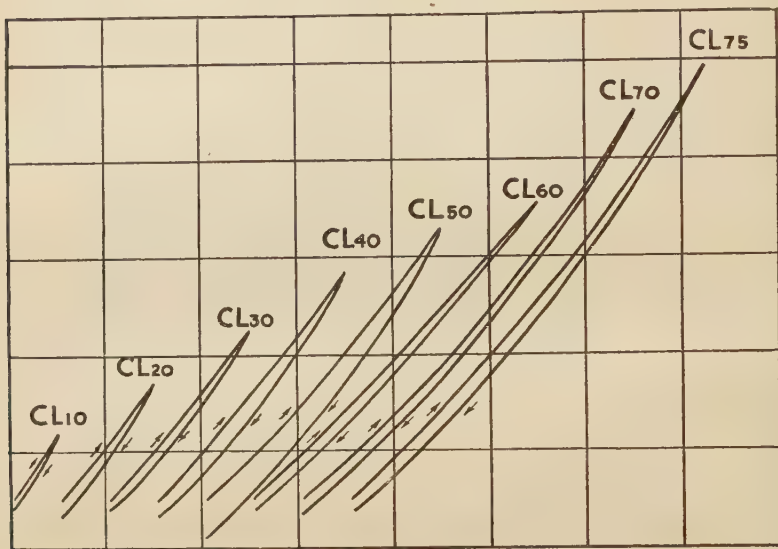


FIG. 4i

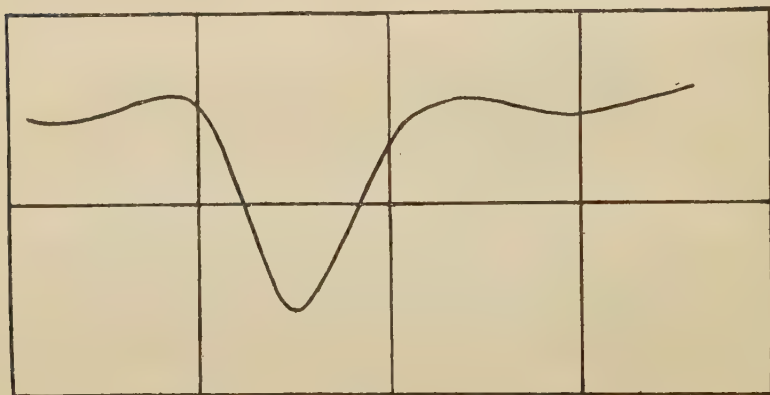


FIG. 5.

One specimen, G.L.1, was treated by hardening in the dilatometer, being cooled from 830° C. in fifteen minutes. This speci-

men was then tempered at 600° C. until it attained to a constant length. This occurred after three heatings and coolings, and the net change of length was a contraction of 13 scale divisions. This is quite in accordance with the changes produced in the corresponding specimens hardened in air outside the dilatometer and then tempered in the instrument.

It is interesting to compare the net changes of volume brought about by the tempering of the specimens cooled in air herein reported and those cooled slowly in the dilatometer as reported in 1922. The necessary values are shown in Table I.

TABLE I.

Tempering Temperature. °C.	Net Change of Length, Scale Divisions.	
	Air Cooled.	Dilatometer Cooled.
100	— 3	— 5
200	— 10	— 6
300	— 14	— 15
400	— 10	— 15
500	— 20	— 16
600	— 10	— 15
700	— 5	...
750	— 2	...

It is evident from the figures given in Table I. that but little difference is produced in the final behaviour of the specimens by the two treatments employed previous to the repeated temperings. The main difference is found in the route by which the specimen arrives at this final volume. In the specimens slowly cooled and tempered at the lower temperatures there is an expansion in the early stages of tempering which is not evident in the behaviour of the fully air-hardened specimens.

The third subject that was examined was the effect of cooling the steel from different temperatures. The experiments were varied in a good many respects in order to determine the effect of the various factors. The variants were the maximum temperature employed, the period of soaking at this temperature, and the rate of cooling therefrom. The temperatures varied between 830° and 950° C., the period of soaking between nothing and two hours, and the time of cooling from the maximum temperature



between fifteen minutes and six hours. It is recognised that in the rapid cooling there is probably some small hysteresis between the volume records and the temperature readings. This is not likely to affect anything on the curves except the apparent temperatures at which the critical volume changes occur, and certainly not to affect the magnitude of the volume changes in any way.

The first series of curves was obtained by cooling specimens at the ordinary cooling speed of the dilatometer from the various temperatures chosen without any soaking at the high temperatures. All the specimens were hardened in the air from  $830^{\circ}\text{C}$ . before being introduced into the dilatometer. The temperatures at which the specimens were treated were respectively  $830^{\circ}$ ,  $850^{\circ}$ ,  $900^{\circ}$ , and  $950^{\circ}\text{C}$ . The curves obtained in these treatments are shown in Fig. 6. The curves show that the effect of simply heating to and cooling from different temperatures is not greatly affected by the temperature actually chosen. The temperatures at which the critical changes occur are the same whatever the maximum temperature to which the steel was heated. There is a slight increase in expansion in the specimens heated to the higher temperatures, but this again is not very marked.

The next series to be considered is that of specimens treated at  $850^{\circ}\text{C}$ ., but cooled at different speeds and previously soaked for different periods. The series comprises the following specimens, all of them having been hardened in the air from  $830^{\circ}\text{C}$ . before insertion in the dilatometer:

- D.L.1.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, not soaked, and cooled slowly.
- D.L.2.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, soaked for one hour, and cooled slowly.
- D.L.3.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, not soaked, and cooled in fifteen minutes.
- D.L.4.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, soaked for one hour, and then cooled in fifteen minutes.
- D.L.5.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, soaked for two hours, and cooled in fifteen minutes.
- D.L.6.—Heated to  $850^{\circ}\text{C}$ . in the dilatometer, not soaked, and cooled in thirty minutes.

The curves illustrating the heating and cooling of all these series of specimens are shown collectively in Fig. 7. The curves indicate that differences in the period of soaking have a distinct effect upon the subsequent expansion of the material. When the steels are not soaked, and particularly when they are cooled

slowly after no soaking, there is an expansion at the critical temperature to a volume even larger than that of the air-hardened

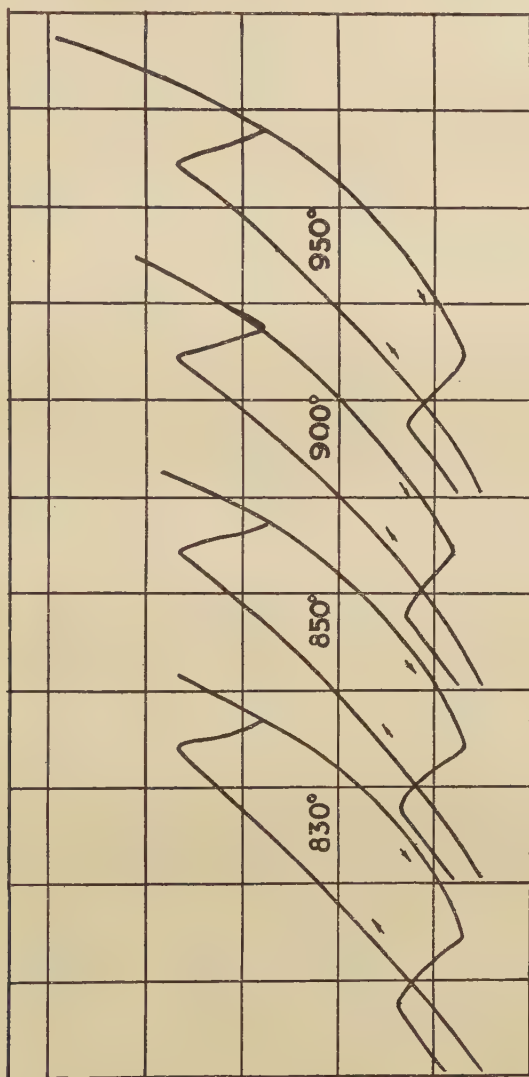


FIG. 6.

material. When the material is soaked there is no such expansion, and the volume of the steel on cooling after such soaking is

generally less than that of the specimen cooled in the air. The effect is rather striking.

The experiments corresponding with those shown in Fig. 7, but made by heating to other temperatures, comprised the following :

- E.L.1.—Heated to 900° C. in the dilatometer, not soaked, and cooled slowly.  
 E.L.2.—Heated to 900° C. in the dilatometer, soaked for one hour, and cooled slowly.  
 E.L.3.—Heated to 900° C. in the dilatometer, soaked for one hour, and cooled in fifteen minutes.  
 F.L.1.—Heated to 950° C. in the dilatometer, not soaked, and cooled slowly.  
 F.L.2.—Heated to 950° C. in the dilatometer, soaked for one hour, and cooled slowly.  
 F.L.3.—Heated to 950° C. in the dilatometer, soaked for one hour, and cooled in fifteen minutes.

The curves obtained from the specimens heated to and cooled from 900° C. are shown in Fig. 8, whilst those obtained at 950° C. are shown in Fig. 9. The curves show that the steels when soaked for any prolonged period at the high temperatures employed for heating do not expand so much at the critical temperatures as when they are cooled at once. This applies both to the specimens heated to 900° C. and those heated to 950° C.; whereas those cooled at once occupy a volume after reheating that is greater than the specimens hardened in the air from 830° C., those soaked show a smaller volume. This applies to those that have cooled quickly and those that have cooled slowly. The effect is slightly more marked at 950° than at 900° C., the latter temperature approximating rather more in its effect to that of 850° C.

On these specimens treated for different periods at various temperatures and cooled at different speeds, tempering tests have also been made. The experiments have all been carried out at 600° C., the specimens being reheated successively until the length became constant. The results of the tests on the specimens heated to 850° C. are shown in Table II.

TABLE II.

Soaking Time. Minutes.	Cooling Time. Minutes.	Number of Reheatings.	Change of Length. Scale Divisions.
nil	360	3	— 12
60	360	1	nil
nil	15	3	— 9
60	15	3	— 5
120	15	1	nil

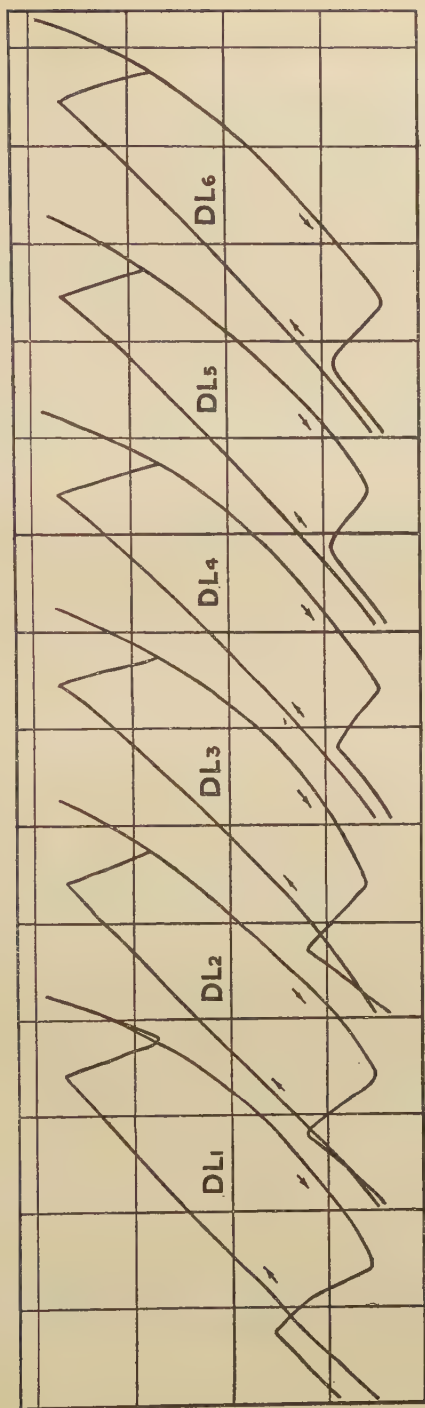


FIG. 7.

It would appear from the results in Table II. that if the specimen has soaked at the high temperature for a prolonged period the resulting article is not very prone to any subsequent

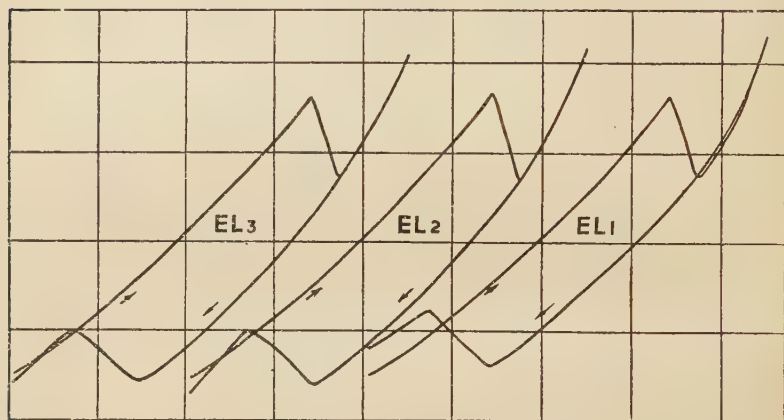


FIG. 8.

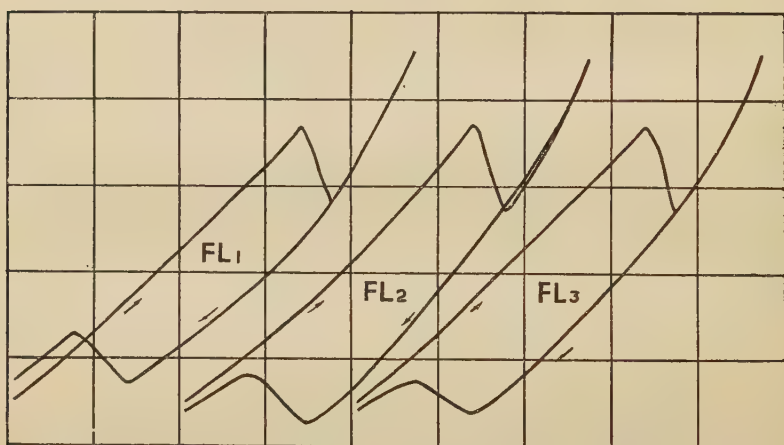


FIG. 9.

change of length on tempering. If the cooling after soaking is very rapid there may be a change of volume on tempering, but if the soaking has been long enough the effect of the rapid cooling is



counteracted. Both soaking and slow cooling reduce the subsequent volume change on tempering, and the soaking appears to be able to neutralise in a measure the rapid cooling. The absence of soaking is not, however, compensated for entirely by slow cooling.

The corresponding effects of tempering those specimens that were variously treated at 900° C. and 950° C. are given in Tables III. and IV. respectively.

TABLE III.

Soaking Time. Minutes.	Cooling Time. Minutes.	Number of Reheatings.	Change of Length. Scale Divisions.
nil	360	2	— 12
60	360	1	nil
60	15	1	nil

TABLE IV.

Soaking Time. Minutes.	Cooling Time. Minutes.	Number of Reheatings.	Change of Length. Scale Divisions.
nil	360	2	— 10
60	360	1	nil
60	15	1	nil

It would appear from these tests that heating to temperatures above 850° C. has an effect similar to that of increasing the period of soaking at the lower temperature. This result might reasonably be expected.

The principal conclusions that can be drawn from these experiments (apart from the previously mentioned conclusion that the longitudinal and lateral expansion are the same) appear to be connected with the formation and stability of austenite and the considerable sluggishness of the formation of sorbite. The fact that the exposure of the steel to higher temperatures, and particularly when the exposure is prolonged, produces a state of the metal which expands less on cooling either quickly or slowly, is probably associated with the production of a thoroughly stable austenite—or it may be that only such a treatment produces austenite completely. The austenite produced

under these conditions is more stable and appears to change to martensite rather reluctantly (hence the smaller expansion).

The low-temperature heatings undoubtedly cause, first of all, a more complete martensite change—causing therefore an initial expansion; and then the gradual breakdown of the martensite by the agglomeration of the carbides that are thrown out of solution produces a contraction. This is the main and final result of the tempering. The heating to lower temperatures, of course, does not produce the same degree of contraction as tempering at 600° C. This is found to be true of all the experiments, some of which are not reported herein. It is noted that the specimens cooled slowly in the dilatometer and then reheated to low temperatures expand and finally contract. Those cooled in the air and then tempered, however, contract from the start, and finally arrive at the same volume as those slowly cooled. No explanation of this difference, which is thoroughly well authenticated by numerous experiments, can be suggested.

The apparent stability of the specimens soaked at high temperatures and then tempered at 600° C. is partly due to the high tempering temperature. The small contraction of the specimens hardened in air and then tempered at 700° or 750° C. suggests that the Ac point in these steels starts at a low temperature and is well spread out.

It appears fairly certain that air-hardening nickel-chromium steels as ordinarily heat-treated are by no means in a stable volume condition. By hardening from a high temperature and soaking well greater stability can be introduced, but, after ordinary hardening, the tempering must be extended for a long time in order to produce complete stability of dimensions.

## CORRESPONDENCE.

Mr. W. T. GRIFFITHS (Woolwich) wrote that he was greatly interested in the paper of Dr. Aitchison and Mr. Woodvine, as he had had occasion to take a considerable number of dilatation curves on nickel-chromium and other special steels, using a dilatometer similar to that employed by the authors. One difficulty he had experienced

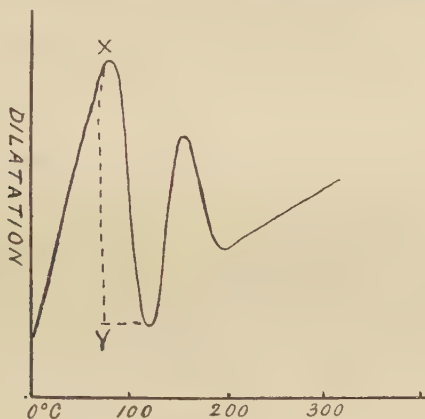


FIG. A.

was due to the fact that the silica tubes conveying the change of length of the specimen to the diaphragm did not expand and contract regularly on heating and cooling, but exhibited abnormalities similar to those shown by steel. The attached figure showed one curve obtained on cooling from 320° C. when the usual steel specimen was replaced by a 2-inch length of opaque silica tubing similar to that used in the dilatometer. The distance XY was approximately equivalent to 0.001 inch. The changes shown were of course larger than would be visible on a curve taken with a steel specimen in the furnace, as they would then be spread out very much, owing to various parts of the long silica tubes reaching the change-point temperatures at differing times. The disturbing feature of those silica changes was that they did not appear to repeat themselves to the same extent on heating and cooling curves and after differing treatments, and he had been unable to make any suitable allowance for them on his curves. The authors attached no scale to their curves, so that no idea could be gained of how those would be affected by changes of the above order, and he would be interested to hear whether it had been found necessary to take any account of the transformations in the silica. It might be of interest to repeat that the difficulties had been overcome to some extent by using tubes of fused transparent silica in which the changes were visible to a much less extent.

Mr. Griffiths also wished to have some further information concerning curves C.L. 70 and C.L. 75 in Fig. 4, p. 280. In Figs. 6 to 9 the authors showed a number of heating curves on each of which the pronounced contraction usual at the Ac point was visible, and from their previous paper it could be ascertained that the contraction started at  $685^{\circ}\text{C}$ . and ended at  $745^{\circ}\text{C}$ . Yet curves C.L. 70 and C.L. 75 showed no sign of this contraction on heating. Similar remarks applied to the absence of the Ar" expansion on cooling. The condition of the steel, namely, air-hardened from  $830^{\circ}$ , was the same as that before several of the curves in Figs. 6 to 9, and some explanation would appear necessary as to why the transformations took place in the one case and not in the other. Further, the deduction drawn on p. 288 from curves C.L. 70 and C.L. 75 that "the small contraction of the specimens hardened in air and then tempered at  $700^{\circ}$  and  $750^{\circ}\text{C}$ . suggests that the Ac point starts at a low temperature and is well spread out in these steels," would seem to be unnecessary in view of the curves in figures 6 to 9.

On p. 288 the authors stated that the initial expansion that they obtained on low-temperature heating was due to a "more complete martensite change," presumably from austenite to martensite. That, however, did not appear to agree with the fact that specimens more rapidly cooled (in air) did not show this initial expansion. One would expect a greater quantity of austenite in the more quickly cooled specimens.

Finally, it was suggested that the value of the paper would be greatly enhanced if the hardnesses of the steels before and after the various treatments could be added. It would then be possible to form some idea as to the nature and extent of the effects produced by the treatments.

Dr. AITCHISON and Mr. WOODVINE wrote in reply to Mr. W. G. Griffiths that the matter of the expansion of the silica tubes had been considered carefully throughout, and some results similar to those reported by Mr. Griffiths were obtained. It was found, nevertheless, that the behaviour of the silica tube was sufficiently regular to allow of a correction being made on the dilatometric records produced by the various steels tested. That correction had been made on the various curves.

The other points mentioned by Mr. Griffiths had been noticed by the authors, who were just as much puzzled by them as Mr. Griffiths himself. If the necessary time had been available, the matter would have been investigated thoroughly, but the pressure of other work compelled the authors to draw the present series of experiments to a close, and therefore deprived them of the opportunity of investigating such points as Mr. Griffiths has raised. The same remarks applied to the Brinell hardness determinations, some of which were made and some of which were left incomplete, so that it was impossible to include an account of those determinations in the paper.

## Iron and Steel Institute.

### THE EFFECT OF CHANGES IN TOTAL CARBON AND IN THE CONDITION OF CARBIDES ON THE SPECIFIC RESISTANCE AND ON SOME MAGNETIC PROPERTIES OF STEEL.

BY PROFESSOR E. D. CAMPBELL AND G. W. WHITNEY  
(ANN ARBOR, MICH., U.S.A.).

THAT hardened steel is a solid solution was clearly recognised by A. Mathiessen.<sup>1</sup> That the atomic relations existing between solute and solvent are essentially the same in solid as in liquid solution has become increasingly apparent during the past twenty-five or thirty years. It is now generally recognised that since steel is a solution, most of its physical properties will depend primarily on the composition and concentration of the dissolved solutes. While carbides are pre-eminently the characteristic solutes in steel, the composition of the carbides will depend not only on the total carbon, but also on the composition and concentration of such elements other than iron as may be present. In order to determine with accuracy the effect of changes in the total carbon content of steel on certain physical properties, such as electrical, thermal, or magnetic, it is necessary to have steel in which the ratio of all elements other than carbon is kept constant, while the carbon alone is varied. It is not possible from commercially produced steel to select sets of bars which differ from each other only in carbon content, and therefore it became necessary to devise a laboratory method by which such bars could be made for research work.

The objects of the present paper are: (1) To outline a method for preparing, on a laboratory scale, small steel bars differing only in carbon content and—to a negligible extent—in sulphur, and (2) to give the results of measurements of specific resistance and some magnetic measurements on annealed and oil-hardened bars.

The only series of pure iron-carbon alloys so far described in

<sup>1</sup> *British Association for the Advancement of Science*, 1863, p. 37.



the literature is the one prepared by the Bureau of Standards, Washington, D.C. A full description of this, and of a series of iron-carbon-manganese alloys prepared at the same time, is given in *Scientific Papers*, Nos. 453, 463, and 464 of that Bureau. These two remarkably complete series were prepared in 3-lb. lots, by melting electrolytic iron in a vacuum furnace in magnesia crucibles. After fusion of the iron, carbon was added, and when desired, manganese.

When carbon is the only element other than iron, it is comparatively simple to make a series such as that made at the Bureau of Standards. However, when the alloy is to contain one or more elements in addition to iron and carbon, it has not been practicable heretofore to produce alloys in which the carbon content can be varied while the ratio of all other elements to the solvent iron remains constant. While in the best practice heats of steel are repeatedly produced in which the elements other than carbon may be kept within a variation of about 0.05 per cent. from the point aimed at, such uniformity is not practicable when the carbon content is varied widely, so that bars differing only in carbon content are not available to those engaged in research work on the constitution of steel.

It was in order to have small bars differing only in carbon content for research purposes that a method for making such bars has been developed. In all the research work on the constitution of steel carried on in this laboratory during the past thirty years, the essential unity of atomic relation between solute and solvent in steel with that of ordinary aqueous solution, has always been kept in mind and has formed the basis for systematic experimental work. The "Force Field Dissociation Theory of Solution"<sup>1</sup> was the logical result of the recognition of steel as a solution in the strict sense of the word.

This theory was formulated in order to give a rational explanation for chemical reaction and reactivities in any solution, whether liquid, solid, or gaseous, and is applicable to either metallic solutions or to those in which the solvent is a non-conductor of electricity.

<sup>1</sup> *Transactions of the Faraday Society*, 1921, vol. 16, Part 3, p. 554.

## MATERIALS USED.

Since no adequate supply of electrolytic iron was available, the next best material was Armco iron, which was furnished by the American Rolling Mills Company in the shape of  $\frac{1}{4}$  inch thick pieces all cut from an 8-inch wide plate which had been rolled from a billet representing the lower third of an ingot. This iron is designated "IN5." The source of the chromium steels was a stock of  $1\frac{1}{4}$  in.  $\times$   $\frac{3}{8}$  in. bars of chromium magnet steel furnished by the Penn Seaboard Steel Corporation and designated "T53." From the steel after annealing, and from the ingot iron, small bars were machined out, these bars being 6 millimetres square, and of such length that short pieces could be cut off at the ends and leave the finished bars 15 centimetres long. These short pieces were useful in making microscopic examinations in order to examine for homogeneity of cross-section. The chemical composition of these base metals is given in Table I. The weight per cent. is given in the upper half and the atomic concentration in milatoms per cubic centimetre in the lower half of the table.

TABLE I.—*Analysis of Materials.*

Bar.	C.	Mn.	P.	S.	Si.	Cr.	Ni.	Cu.	Fe.
IN5 (wt. %)	0.015	0.024	0.005	0.023	trace	...	...	0.042	99.89
T53 (,, ,)	0.85	0.24	0.027	0.035	0.25	2.23	0.12	0.084	96.16
IN5 (at. conc.)	0.10	0.03	0.013	0.056	...	...	...	0.05	139.85
T53 (,, ,)	5.56	0.34	0.068	0.086	0.64	3.37	0.16	0.10	134.62

## PREPARATION OF SPECIMEN BARS.

The three principles involved in the preparation of the specimen bars were: (1) Carburisation with suitable carburising mixture under controlled time and temperature; (2) decarburisation with moist hydrogen at  $950^{\circ}\text{C}$ .; (3) establishment of an equilibrium in carbide concentrations by holding in dry  $\text{H}_2$  at  $950^{\circ}\text{C}$ . two steels differing widely in carbon content.

*Carburisation.*—Carburisation by heating iron with wood charcoal, animal charcoal, or other organic material, has been

practised for centuries, having formed the basis of the old cementation process for making steel, and is still very extensively practised in case-hardening. In this process the carburisation is largely effected through the action of gaseous carbon compounds. The carburising mixture used in the present work consisted of 50 per cent. wood charcoal, 25 per cent. animal charcoal, and 25 per cent. barium carbonate. About 6 kilos of such a mixture was placed in a porcelain-lined ball mill and ground for two hours in order to ensure fineness and homogeneity of the mixture.

From twenty to twenty-two small bars were wired together with soft iron wire, one near each end of the bars, in such a way that the bars were held parallel and about 5 or 6 millimetres apart, thus forming a sort of grid. This grid was then rolled into a cylinder which could be placed in a cylindrical carburising pot, leaving about a centimetre clearance between the grid and the inside of the pot. This pot was made of high-temperature resistant alloy and was 23 centimetres high by 10 centimetres outside diameter, with walls 1 centimetre thick. It was lined with one layer of sheet iron against the side and bottom, and provided with a cover made of the same material, having a hole through which a closed porcelain tube may be inserted to the bottom of the pot. This permits the insertion of a platinum-platinum-rhodium thermocouple, by means of which the temperature is measured. The porcelain tube is long enough to reach to the outside air, thus ensuring an oxidising atmosphere immediately around the couple, although the bead is far enough down to measure accurately the temperature at a point 7 or 8 centimetres from the bottom of the pot. In preparing for carburisation, a layer of carburising mixture is first poured in and the cylindrical grid of bars inserted, care being taken to see that the grid is centred in order to ensure uniformity of temperature for all the bars. The porcelain tube is then set in place and the pot filled with carburising mixture, taking care to see that the mixture is uniformly packed. When the whole has been packed, about 500 grammes of the carburising mixture being required, the cover is placed on and luted with a finely ground mixture of four parts silica and one part clay. The pot used for carburising can be used equally well for slow annealing of steel by merely substituting pure finely ground and ignited alumina for the carburising mixture in packing.

The furnace used for carburising has a heating unit consisting of an electrically wound alundum cylinder 15 centimetres inside diameter and 30 centimetres high, thus giving a clear heating chamber of these dimensions. This heating unit is thoroughly insulated from radiation losses, and the furnace is so designed as to facilitate repairs when the heating coils burn out. This furnace has been in use with only slight changes for more than ten years, having been found very convenient, as it can be changed over in a few minutes from one for carburising or annealing into one for heating bars for hardening.

When the pot containing the bars to be carburised had been luted, it was placed in the heating chamber on three small pieces of porcelain, in order to raise it a few millimetres from the bottom, care being taken to centre the pot in the cylindrical heating chamber. The space in the heating chamber around and above the pot was then filled by pouring in coke screenings, the upper portion of the coke being mixed with spent carburiser from a previous charge. When the heating chamber had been thus filled, asbestos paper was laid over the coke and followed by two pieces of sheet iron notched to permit the porcelain tube to project through. Another layer of asbestos paper was laid on top of the sheet iron and was held down with a couple of bricks. The thermocouple was then inserted in the slightly projecting tube and the current turned on. With a little experience, the voltage necessary to bring the furnace to a desired temperature can be determined, and the temperature will be reached in about eighteen to twenty hours. When the carburisation had continued for any desired length of time, usually from one to three days, the switch was opened and the furnace allowed to cool. Some carburisations were carried on at as high as  $1000^{\circ}\text{C}.$ , and in some cases the current was reduced so as to bring the temperature to about  $840^{\circ}\text{C}.$  and held at that temperature for one or two days, to allow time for diffusion of carbides without greatly increased carburisation before the switch was opened and the furnace allowed to cool to room temperature. Before pulling the switch, the covering of the furnace was slightly raised, so that a layer of crushed charcoal or carburising mixture could be placed on the surface of the partially burned coke. When the temperature of this charcoal has reached that of the furnace, enough reducing



gases will have been produced to ensure a strong reducing atmosphere during cooling. The switch is then opened and the furnace allowed to cool to room temperature. By these means the bars received what in this paper is termed a "slow anneal," as more than three hours are required for the temperature to fall through the first  $200^{\circ}$ , and the temperature will be above  $100^{\circ}$  C. after twenty-four hours' standing.

Before wiring together the small bars to form a grid, all bars were carefully smoothed, stamped, and numbered for identification, and washed with ether to remove traces of oil, dried, and accurately weighed to the nearest milligramme. After the carburisation had been completed and the furnace cooled to room temperature, the bars were removed. The wires of the grid were then cut, the bars separated and thoroughly washed with water—rubbing with a cloth until clean—and then washed with alcohol followed by ether, dried and weighed to determine the gain in weight due to absorption of carbon. When an experiment has been conducted as above described, the bars will show no change in appearance, except the change from the white colour of ingot iron to the characteristic colour of high-carbon steel. Analysis of these bars for sulphur and phosphorus showed absolutely no gain in either of these elements over that originally present in the bars. The results of the carburisation of a single set of twenty bars of "IN5" form a typical example of the uniformity in carbon content which may be expected from this method of carburisation. The percentage gains in weight of these twenty bars were as follows: 1.301, 1.294, 1.290, 1.290, 1.281, 1.279, 1.290, 1.313, 1.297, 1.285, 1.288, 1.293, 1.302, 1.300, 1.302, 1.297, 1.273, 1.281, 1.267, 1.277.

The average of these is 1.290 per cent., to which would have to be added 0.015 per cent., the original carbon content of the iron before carburisation. It will be noted that the maximum deviation of the highest and lowest bars is  $\pm 0.023$  per cent. from the average of all twenty.

The certificate of the Bureau of Standards, giving the analysis of electric steel, Standard Sample No. 51, gives the average carbon as 1.29 per cent. Twelve chemists co-operated. The results of the twelve individual reports, in the order given on the certificate, are as follows: 1.28, 1.28, 1.32, 1.29, 1.28, 1.26, 1.30,



1.30, 1.27, 1.30, <sup>1.30</sup><sub>1.29</sub>, 1.28; average, 1.29 per cent. It will be noted that the maximum deviation of the highest and lowest values reported is 0.03 per cent. from the general average.

*Decarburisation.*—The principle involved in the preparation of decarburised bars is that first described by one of the authors five years ago, in an article on the decarburisation of steel with hydrogen.<sup>1</sup> In the present work the decarburised bars were prepared in the same furnace and under essentially the same conditions as those described in detail in an article dealing with decarburisation, submitted to the Institute a year ago.<sup>2</sup> The following method was the one used in the preparation of decarburised bars. The necessary number of small bars were stamped, cleaned, and accurately weighed, after which they were formed into a bundle by binding together with fine pure iron wire. In making up the bundle care was taken that all bars were separated from one another by at least the diameter of the wire used to bind them together. Usually about thirteen 6-millimetre square bars were treated at the same time. The bundle of bars was inserted to the centre of the reaction chamber, and heated at 950° C. to 960° C. in a stream of moist hydrogen for seven days. At the end of this time pure dry hydrogen was substituted for the moist and allowed to flow until it was judged all water had been removed, after which the outlet stop-cock of the reaction tube was closed, the current cut off, and the furnace allowed to cool over-night with a slight plus pressure of hydrogen in the tube. The bars, when removed from the furnace, should be perfectly free from any signs of oxidation. This will be the case if all moisture had been removed by the dry hydrogen before allowing the furnace to cool. Small amounts of moisture remaining will react with the bars when the furnace is cooling, causing more or less discoloration at the ends of the bars. The extent of the decarburisation may be computed by the loss of weight of the bars, but the actual percentage of carbon remaining should be checked by combustion on cuttings from one of the bars. In the decarburisation there is a loss of part of the sulphur originally present in the bars, this loss

<sup>1</sup> E. D. Campbell, *Journal of the Iron and Steel Institute*, 1919, No. II. p. 407.

<sup>2</sup> E. D. Campbell, "The Relative Efficiency of Dry and Moist Hydrogen on the Decarburisation of Steel at 950° C.," *Journal of the Iron and Steel Institute*, 1923, No. II. p. 179.

amounting in many cases to three-fourths of the total sulphur present. Of the elements usually reported in steel, carbon and sulphur alone are removed by the action of either moist or dry hydrogen.

*Equilibrium in Dry Hydrogen.*—The principle involved in this method is that if two solutions differing widely in carbon concentration are held in a still atmosphere of pure dry hydrogen at a temperature of about  $950^{\circ}\text{C}$ .—that is, well above the C3 point of pure iron—hydrogen will tend to combine with carbon of the dissociated carbides, removing it in the form of hydrocarbons. These compounds coming into contact with the solution of low-carbon concentration, will react, the hydrocarbons giving up their carbon with liberation of hydrogen. There are thus two reversible reactions, and theoretically there should be an equilibrium established between the carbide concentrations of the two solid solutions and the hydrocarbon concentration in the gas. Since the reaction between gaseous hydrocarbons takes place at the surface of the low-carbon solution, and since the solutions are solid, time will be required for the resulting solution to become homogeneous throughout the entire cross-section, as diffusion in such solid solutions must necessarily proceed much more slowly than in liquid solutions. In a previous paper<sup>1</sup> dealing with this iron-iron carbide equilibrium, it was shown that equilibrium was almost established after five days, a cross-section of a 6-millimetre square bar showing a small area of only about 1 millimetre in diameter in which the carbides were not quite so uniformly diffused as they were in the remaining 97 per cent. of the bar. Holding for seven days ensures complete uniformity in distribution of carbides, and in all the work reported in this paper this time was adopted as the one at which bars were held before cooling down to room temperature. In setting up an equilibrium experiment, the desired number of bars of each of the two steels, after cleaning and accurately weighing, were made into a bundle in the same way as was done for decarburisation with hydrogen. Care was taken to distribute the two sets of bars as symmetrically as practicable in the bundle in such a way as to facilitate uniformity of distribution of the carbides. The bundle of bars was inserted in

<sup>1</sup> "The Iron-Iron Carbide Equilibrium in Dry Hydrogen at  $950^{\circ}\text{C}$ ," *Journal of the Iron and Steel Institute*, 1923, No. II. p. 173.

the centre of the reaction chamber of the same furnace as that used for decarburising with moist hydrogen and for the iron-iron carbide equilibrium to which reference has already been made. The temperature of the furnace was kept constant at  $950^{\circ}$  to  $960^{\circ}$  C. for seven days, after which the furnace was allowed to cool, so that the bars removed from the furnace were annealed. If the current were cut off entirely the drop in temperature for the first  $200^{\circ}$  required about one hour, and the furnace would be down to room temperature by morning if the cooling were begun late the previous afternoon.

In this paper, annealing under these conditions is termed "medium" annealing. In some cases "very slow" annealing was desired. In such cases the heating current was reduced, so that the temperature would fall gradually during twenty-four hours from  $950^{\circ}$  C. to  $750^{\circ}$  C., after which the current was further reduced, so that about six hours were required to pass from  $750^{\circ}$  C. to  $670^{\circ}$  C., when the current was cut off and the furnace allowed to cool over-night.

The loss of carbon of the high-carbon bars was computed from the loss in weight of each bar, and the increase in carbon of the low-carbon bars computed from their percentage increase in weight.

The data obtained from two typical equilibrium experiments show the results that can be expected from the method.

Five of the twenty carburised bars of "IN5," given under the description of carburisation, were made into a bundle with eight "IN5" original bars. After the conclusion of the equilibrium experiment, the carbon content of the five bars, computed by subtracting the percentage loss of weight of each bar from its carbon content, gave the following values: 0.600 per cent., 0.601 per cent., 0.597 per cent., 0.600 per cent., and 0.602 per cent. The percentage gain in weight of four IN5 bars nearest to the high-carbon bars was 0.449 per cent., 0.454 per cent., 0.450 per cent., 0.451 per cent. The percentage gains of the four IN5 bars on the outer part of the bundle were 0.414 per cent., 0.418 per cent., 0.417 per cent., 0.412 per cent. The net loss of carbon computed by deducting the gain of weight of the low-carbon from the loss in weight of the high-carbon bars was 0.013 per cent. of the total weight of bars.

In another equilibrium experiment four bars of T53 were made into a bundle with nine bars of IN5. At the conclusion of the experiment the carbon content of the four T53 bars, computed, by deducting their percentage loss in weight from the original carbon content, gave 0.385 per cent., 0.348 per cent., 0.354 per cent., and 0.353 per cent. The carbon contents of the nine IN5 bars, computed by adding the percentage gains to the original carbon content of 0.015 per cent., were as follows: 0.228 per cent., 0.229 per cent., 0.226 per cent., 0.229 per cent., 0.227 per cent., 0.227 per cent., 0.227 per cent., 0.230 per cent., 0.229 per cent. There was no appreciable loss of carbon in this experiment.

By utilising the three reactions—carburisation, decarburisation, and equilibrium—enough bars were prepared, so that two sets of ten derivatives of IN5 and two sets of seven derivatives from T53 were selected for measurement of properties. One set of each was used in the annealed condition as prepared, and the other two were hardened by quenching from 900° C. in oil. The method of heating the bars prior to quenching was the same as that used in this laboratory for similar purposes for several years past. Oil was substituted for water, in order to study the effect of a less drastic quenching. It was found when oil was used the time required for a bar to lose its red colour after immersion was increased from about one second, in the case of water quenching, to three or four seconds in case oil was used. Since in each series of derivatives the carbon alone is varied from that in the base metal, only the carbon in weight percentage and atomic concentration in milatons per cubic centimetre will be given for the two sets of derivatives in tabulation of specific resistance measurements.

*Specific Resistance.*—Measurements of specific resistance were made with the bars immersed in an oil-bath which was maintained at 25° C. with a variation of less than 0.01°. The fall in potential over knife-edges 10 centimetres apart was measured by means of a Leeds and Northrup precision potentiometer, and the milliammeter readings were checked by measuring the fall in potential over a standard 0.001 ohm resistance, certified by the Bureau of Standards. The cross-section of each bar was obtained by making ten measurements in each direction by means of a precision micrometer. The mean of the ten measurements in each direction



was used to compute the cross-sections. The results of the specific resistance measurements are given in Table II. In this table are given the weight percentage and atomic concentration of carbon, the rate of annealing, the specific resistance of annealed and hardened bars, and the increase due to hardening.

TABLE II.—*Specific Resistance.*

Bar.	Carbon.		Rate of Annealing.	Specific Resistance.		
	Wt. per Cent.	Atomic Conc.		Annealed.	Hardened.	Increase due to Hardening.
IN5, No. 1	0	0	Very slow	10.48	10.63	0.15
" " 2	0.11	0.7	Medium	10.93	10.99	0.06
" " 3	0.23	1.5	"	11.35	11.58	0.23
" " 4	0.45	3.0	"	12.12	14.46	2.34
" " 5	0.60	3.9	"	12.66	19.19	6.53
" " 6	0.82	5.4	"	13.54	24.99	11.45
" " 7	0.97	6.3	"	14.00	29.19	15.19
" " 8	1.02	6.7	Slow	14.80	34.04	19.24
" " 9	1.19	7.8	Medium	15.52	38.81	23.29
" " 10	1.30	8.5	Slow	16.16	37.37	21.21
T53, No. 1	0.04	0.24	Very slow	29.19	30.04	0.85
" " 2	0.36	2.4	Medium	26.21	34.12	7.91
" " 3	0.50	3.3	"	25.03	38.12	13.09
" " 4	0.85	5.6	Slow	23.79	43.81	24.12
" " 5	1.05	6.9	Medium	25.99	48.91	22.92
" " 6	1.43	9.4	"	27.03	50.31	23.28
" " 7	1.62	10.6	Slow	27.72	52.09	24.37

*Open Pole Magnetic Measurements.*—There are some reasons why it seemed desirable to make some magnetic measurements on bars with entirely open poles, instead of with a closed magnetic circuit, as is usually done. It was realised that results obtained with open poles must be considered as relative only. If such comparative measurements are made on bars of the same length and cross-section, the results may indicate some of the factors influencing magnetic properties more clearly and convincingly than when magnetic tests are made in the usual manner. It has been well known for many years that a bar of pure iron with open poles loses practically all its magnetism when any magnetising field to which it may have been subjected is cut off. In order to have a permanent magnet it is essential that there be a certain concentration of carbides in solution in the iron. In one of the



author's papers on the force field dissociation theory of solution already referred to, the hypothesis was suggested that permanent magnetism is due to the serial alignment of the electro-magnetic force fields of carbides or other solutes in solution. In a later paper submitted to this Institute<sup>1</sup> the hypothesis was advanced that carbides possess a definite magneto-motive potential which is dependent on the chemical constitution of the carbides, but is independent of the size of the particles in a manner analogous to the electro-motive potential of a cell which also is dependent on the chemical composition but is independent of the size. The hypothesis was also advanced that the open force fields of carbides which, as has been known for some time, cause electrical resistance, can be the cause of magnetic resistance as well. Since the force fields of silicides in solution will produce electrical resistance in a manner similar to that caused by carbides, and yet since silicon steels retain almost no permanent magnetism and possess very low magnetic resistance, one is strongly inclined to think that it is something in the structure of the carbon atom that is responsible for both magneto-motive potential and magnetic resistance. If, therefore, carbides are the dominant factor in determining magnetic properties, measurements of these properties on steels differing from each other only in carbon concentration might be expected to add something to our knowledge of the mechanism of magnetism.

#### APPARATUS USED IN MAGNETIC TESTING.

The magnetic balance used for the present investigation works on the same principle as the one described in a previous paper,<sup>2</sup> but a number of improvements in construction and in technique of handling have been made. The improved balance is shown in Fig. 1.

The magnetic lever (B), which is 6 millimetres square and 15 centimetres long, ends in an octagonal head (A) 15 millimetres in width and length. This bar was made from a piece of electrolytic iron vacuum-fused in magnesia-lined crucibles. The

<sup>1</sup> "Preliminary Magnetic Study of Heat-Treated Carbon Steels," *Journal of the Iron and Steel Institute*, 1922, No. II. p. 201.

<sup>2</sup> "A Preliminary Magnetic Study of some Heat-Treated Carbon Steels," *Journal of the Iron and Steel Institute*, 1922, No. II. p. 201.

rough rolled, long bar from which this lever of the balance was machined out was generously furnished by the Bureau of Standards. When all machine work on the magnetic lever had been completed, it was heated in a slow stream of pure, dry hydrogen at  $950^{\circ}$  for seven days, after which it was very slowly cooled in dry hydrogen. Two days were taken to lower the temperature from  $950^{\circ}$  to  $600^{\circ}$ , after which the current was cut and the lever cooled with the furnace. In the present balance the long balancing screw attached to the end of the magnetic lever is made of alu-

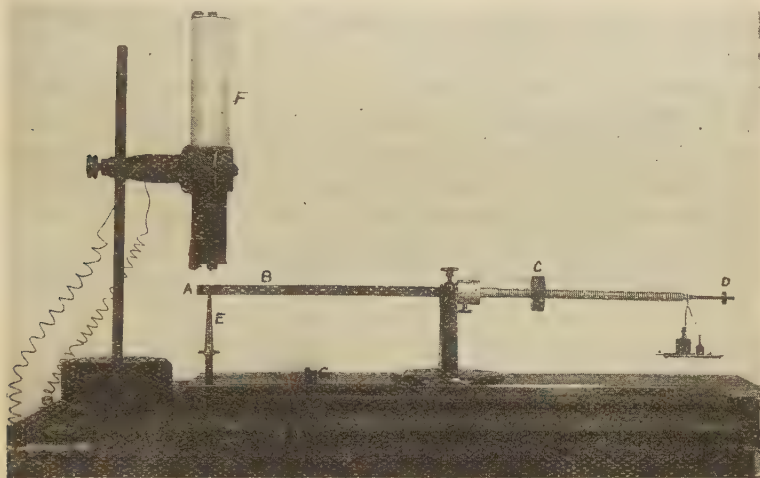


FIG. 1.

minium and is provided with a heavy nut (C), and a small one (D) for fine adjustment. A set of weights reading directly in dynes was made from analytical weights by attaching to them the necessary amount of fine platinum or aluminium wire. The pedestal on which the knife-edges rest, as well as the heavy plate serving as a base and the adjusting screw (E), are made of brass.

The holder (F) was wound over a distance of 146 millimetres of its length in such a way that the magneto-motive force due to a given current could be readily computed and expressed in gilberts per centimetre in length of the bar. The terminals of the holder are connected to a double pole, double-throw switch for controlling the direction of the current. The current, which was

controlled by suitable rheostats, was measured with a standard milliammeter with capacity of 1500 milliamperes. Under most conditions 11.3 milliamperes gave 1 gilbert per centimetre, but by means of a special shunt, when working with low fields, this could be increased to 113 milliamperes to 1 gilbert. The bar to be tested was carefully cut to 15 centimetres and squared at the ends. The cross-piece at the bottom of the holder on which the bar rests is a piece of brass accurately machined to 1 millimetre square, so that the face of the steel bar is exactly 1 millimetre from the under-side of the brass cross-piece. A series of measurements of the attractive force of several magnets was made at distances of 5 millimetres and 10 millimetres between the lower face of magnet and upper face of the head of magnetic lever. On the assumption that the intensity of attractive force between two pole centres is inversely proportional to the square of the distance, it was found that to satisfy the assumption made the combined distance of the pole centres from the end of the magnet and the surface of the octagon would be almost exactly 1 millimetre. Weak and strong magnets gave nearly the same value for the computed distance of the pole centre from the actual end of magnet and face of lever. Accordingly, a distance of 9 millimetres between the lower face of the magnet and the upper face of the lever was adopted, so that the attractive forces reported could be considered as being those at a distance of 1 centimetre between pole centres.

In order to keep the distance between the actual ends of the end of the magnet and the lever constant at 9 millimetres, a brass gauge (G), accurately machined to 8 millimetres in height, was set on the centre of the octagon, and the holder lowered until the gauge block was just in contact with the under-side of the cross wire on which the magnet rests.

When the balance was centred under the holder and the distance accurately adjusted, a bar of carefully annealed electrolytic iron was placed in the holder. A convenient weight, usually 4000 dynes, was placed on the pan, and the system brought into balance by means of the two balancing nuts (C) and (D). The present balance has a range of about 13,000 dynes.

The bar to be measured was first magnetised in a special magnetising coil. This coil consisted of 1004 turns of wire wound

over a length of 25 centimetres on a piece of brass tubing, 15 millimetres inside diameter. The 15-centimetre bar to be magnetised was held in a cylindrical support, intended to keep it in the axial centre. When the bar had been inserted to the longitudinal centre of the magnetising coil, round bars of Armco iron, about 14 millimetres diameter, were inserted at both ends. These bars extended far enough beyond the end of the magnetising coil, so that they could be readily connected by means of a heavy iron yoke, thus closing the magnetic circuit.

When a bar to be magnetised was in position, a small current of about 0.2 ampere was applied and then gradually increased up to 2.5 to 3.0 amperes. The current was then slowly reduced to the minimum value and the process repeated three times. The bar was then removed from the coil and placed in the holder (F) of the balance, with the north pole down. In order to keep a bar centred in the holder, a short collar cut from a suitable size tubing was slipped over the bar at each end. When a bar had been placed in the holder a small magnetising current, giving the same polarity as that of the bar, was put through the holder and the magneto-motive force applied, increased to about 120 gilberts, and then reduced to a small value before repeating. This process was repeated three times to ensure constancy of magnetic condition of the bar at the time of measurement, and the current then cut to zero. The attractive force of the remanent field was measured by removing the 4000 dynes weight from the pan and substituting smaller weights, until the lever which was held down with a finger while changing weights would just not be raised from the adjusting screw on which it rests. The difference between 4000 dynes and the weight added to bring the system in balance again gives the attractive force of the remanent field at a distance of 1 centimetre between pole centres. This attractive force was reduced to that which would be given for a cross-section of 1 square centimetre by dividing the force measured by the cross-section of the bar.

If the carbides or other solutes to which remanent magnetism is due have already been polarised, no further work will be required to polarise them, so that a magneto-motive force of the same polarity as that of the bars will produce an increase in flux and therefore an increase in the attractive force, the increase



being a function of the magnetic resistance of the steel. For convenience, the number of gilberts required to give an increase in attractive force of 3000 dynes per  $\text{cm}^2$ . ( $H_{3m}$ ) was adopted. To measure the gilberts to give 3000 dynes, the attractive force was first measured as previously described, and then enough weights were removed from the pan to be equivalent to 3000 dynes per  $\text{cm}^2$ . When this had been done a magnetising current of the same polarity as that of the bar was put on, and raised or lowered until the system was again in balance. From the milliammeter reading the gilberts ( $H^{3m}$ ) were computed.

To determine the gilberts to demagnetise ( $H_d$ ) the bars, a current of opposite polarity from that of the bar was put through the holder and gradually increased, until after again reducing and breaking the current the bar had just reached the reversing point—that is, a slight increase of the demagnetising current would leave the bar with a weak remanent field of the opposite polarity. Repeated measurements of the gilberts required to demagnetise ( $H_d$ ) were made, each bar being remagnetised, using the coil with the closed magnetic circuit to ensure saturation, that is, polarisation of the carbides each time.

TABLE III.—*Magnetic Measurements.*

Bar.	Carbon.		Dynes per $\text{Cm}^2$ .			$H_{3m}$ .			$H_d$ .		
	Wt. per Cent.	At Conc.	Hard-ened.	An-nealed.	Differ-ence.	Hard-ened.	An-nealed.	Differ-ence.	Hard-ened.	An-nealed.	Differ-ence.
IN5, No. 1	0	0	0	0	0	24.9	24.0	0.9	...	...	...
" " 2	0.11	0.7	110	110	0	27.1	24.9	2.2	13.3	...	...
" " 3	0.23	1.5	320	140	180	29.7	24.9	4.8	20.0	...	...
" " 4	0.45	3.0	1180	195	985	30.2	24.9	5.3	41.0	12.4	28.6
" " 5	0.60	3.9	3835	280	3555	32.9	25.7	7.2	68.4	15.1	53.3
" " 6	0.82	5.4	3805	585	3220	40.5	30.2	10.3	75.0	21.3	53.7
" " 7	0.97	6.3	3225	640	2585	44.8	30.2	14.6	75.9	21.3	54.6
" " 8	1.02	6.7	2750	585	1165	48.4	29.3	19.1	78.2	22.2	56.0
" " 9	1.19	7.8	1670	530	1140	61.7	25.7	36.0	77.3	16.9	60.4
" " 10	1.30	8.5	1640	140	1500	60.2	25.7	34.5	77.3	18.6	58.7
T53, No. 1	0.04	0.24	...	...	...	25.3	25.7	0.4	26.1	12.4	13.7
" " 2	0.36	2.4	3410	500	2910	34.0	30.2	3.8	61.6	20.4	41.2
" " 3	0.50	3.3	4390	1000	3390	32.4	32.0	0.4	65.3	25.7	39.6
" " 4	0.85	5.6	4740	860	3880	35.9	28.4	7.5	72.0	17.8	54.2
" " 5	1.05	6.9	4530	1475	3055	41.9	41.7	0.2	75.0	32.9	42.1
" " 6	1.43	9.4	3505	1140	2365	50.6	38.2	12.4	74.2	30.2	44.0
" " 7	1.62	10.6	3195	975	2220	51.5	29.6	21.9	76.4	25.7	50.7



The results of magnetic measurements made, as described on the IN5 and T53 derivatives in both annealed and oil-hardened condition, as well as the difference in the magnetic properties due to hardening, are shown in Table III.

### CONSIDERATION OF RESULTS.

*Specific Resistance.*—A study of the data given in column 5, Table II., shows that the specific resistance of the pure iron-carbon series in the annealed condition is a linear function of the total carbon content up to a point somewhat above the eutectoid, when there is an abrupt but small increase due to the presence of pro-eutectoid cementite. After this small rise, the curve continues with slightly increased slope compared with that of the first portion. In the chromium steel series, in sample I., the high specific resistance would indicate that most of the chromium is in solution in the solvent iron. With increase of carbon, chromium is precipitated in the form of double carbides or mixed crystals, as is indicated by the lowering of the specific resistance until the eutectoid, sample IV., is passed, after which, due to an increasing amount of pro-eutectoid cementite, the specific resistance again increases with the carbon content.

In the hardened condition, which is necessary in order to have the greatest proportion of the carbides in solution, the specific resistance of the pure iron-carbon series increases more rapidly than the atomic concentration of the carbon, indicating either a lowering of the molecular weight of the carbides with increase of atomic concentration, or a decrease in the stability of the carbides with increasing carbon content. The present results confirm the conclusions drawn from those presented to the Faraday Society in 1917.<sup>1</sup> It is now well recognised that increasing the temperature from which steel is quenched, as well as varying the rate of cooling, will have a marked effect on the specific resistance. The specific resistance of the chromium steels in the hardened condition increases more rapidly than that of the pure iron-carbon series in the low-carbon part of the curve, but bends over as the eutectoid is approached, so that in the upper part of the curve the slope is decidedly less than that of the

<sup>1</sup> *Transactions of the Faraday Society*, 1917, vol. 12, p. 278.

IN5 series. In order to facilitate a comparison of specific resistance and some magnetic properties in the hardened samples, the necessary data are summarised in Table III.

*Magnetic Resistance.*—In a recent article giving the results of measurements made on two sets of four bars each of straight carbon and chromium steels, the measurements having been made by a standard method with closed magnetic circuit, it was shown that the minimum reluctivity is a linear function of the carbon concentration.<sup>1</sup> Under the force field dissociation theory and the hypothesis that carbides in solution can cause magnetic resistance, the magneto-motive forces which must be applied to different bars in order to give an equal increase in flux, as indicated by an equal increase in attractive force, would be proportional to the magnetic resistance of the bars. A comparison of the gilberts required to give an increased attractive force of 3000 dynes per square centimetre ( $H_{3m}$ ) with those for the specific resistance shows that, in general, in each series the  $H_{3m}$  values follow the same order as those for the specific resistance. It will be noted that, although the electrical resistance of the chromium steels is higher than that of the IN5 series of the same carbon content, the magnetic resistance indicated by the  $H_{3m}$  values does not increase as rapidly for the "T53" bars as it does for those of the pure iron-carbon series. This is due to the fact that chromium in solution produces electrical resistivity, but has little or no effect on magnetic resistance. It has been shown by one of the authors<sup>2</sup> that carbides in solution in steel possess a thermo-electromotive potential which is dependent on the concentration of the dissolved carbides. Other solutes in solution possess thermo-electromotive potential, but carbides alone seem to possess, to any considerable extent, magneto-motive potential. In the present case, the gilberts required to demagnetise ( $H_d$ , Table III.) indicate the magneto-motive potential of the carbides in solution in the two series. It will be noted that the  $H_d$  values for the chromium steels rise more rapidly than those of the IN5 series in the lower

<sup>1</sup> A. W. Smith, E. D. Campbell, W. L. Fink, "The Effect of Changes in Total Carbon and in the Condition of Carbides on the Magnetic Properties of Steel," *Physical Review*, March 1924, vol. xxiii. p. 377.

<sup>2</sup> E. D. Campbell, "The Influence of Heat Treatment on the Thermo-Electric Properties and Specific Resistance of Carbon Steels," *Journal of the Iron and Steel Institute*, 1916, No. II. p. 267.

part of the curve, but cross about the eutectoid point, the values for the hypereutectoid bars of the chromium steels being slightly below those of the pure iron-carbon series. If it is true that carbides in solution possess magneto-motive potential which may be made manifest by polarising all in one direction, and if carbides in solution cause magnetic resistance, then the magnetic field at the open pole of a bar magnet might be expected to bear a relation to the ratio of the magneto-motive potential and the magnetic resistance, that is, the ratio of  $H_d$  over  $H_{3m}$ . The ratios of these values for both series of steels in the hardened condition are shown in column 6, Table IV., and the attractive

TABLE IV.—*Hardened Steels.*

Bar.	Carbon.		Specific Resistance.	$H_{3m}$ .	$H_d/H_{3m}$ .	North Pole Field. Dynes per Cm <sup>2</sup> .
	Wt. per Cent.	Atomic Conc.				
IN5, No. 1	0	0	10.63	24.9	0	0
" " 2	0.11	0.7	10.99	27.1	0.49	110
" " 3	0.23	1.5	11.58	29.7	0.67	320
" " 4	0.45	3.0	14.46	30.2	1.35	1180
" " 5	0.60	3.9	19.19	32.9	2.08	3835
" " 6	0.82	5.4	24.99	40.5	1.85	3805
" " 7	0.97	6.3	29.19	44.8	1.69	3225
" " 8	1.02	6.7	34.04	48.4	1.62	2750
" " 9	1.19	7.8	38.81	61.7	1.25	1670
" " 10	1.30	8.5	37.37	60.2	1.28	1640
T53, No. 1	0.04	0.24	30.04	25.3	1.03	...
" " 2	0.36	2.4	34.12	34.0	1.81	3410
" " 3	0.50	3.3	38.12	32.4	2.02	4390
" " 4	0.85	5.6	43.81	35.9	2.01	4740
" " 5	1.05	6.9	48.91	41.9	1.79	4530
" " 6	1.43	9.4	50.31	50.6	1.47	3505
" " 7	1.62	10.6	52.09	51.5	1.48	3195

force in dynes at 1 centimetre distance between pole centres of the north pole field, in column 7. The correlation between the magneto-motive potential, divided by the magnetic resistance ( $H_d/H_{3m}$ ) and the north pole field, is shown graphically in Fig. 2. Under the concept developed in the present research, coercive force, as usually measured, is primarily dependent on the magneto-motive potential of carbides in solution, and hysteresis is principally the work expended in reversing the polarity of the carbides

in solution. Coercive force and hysteresis—due to other solutes, grain-size, or to the state of strain in the iron—is relatively small compared with that due to carbides in solution.

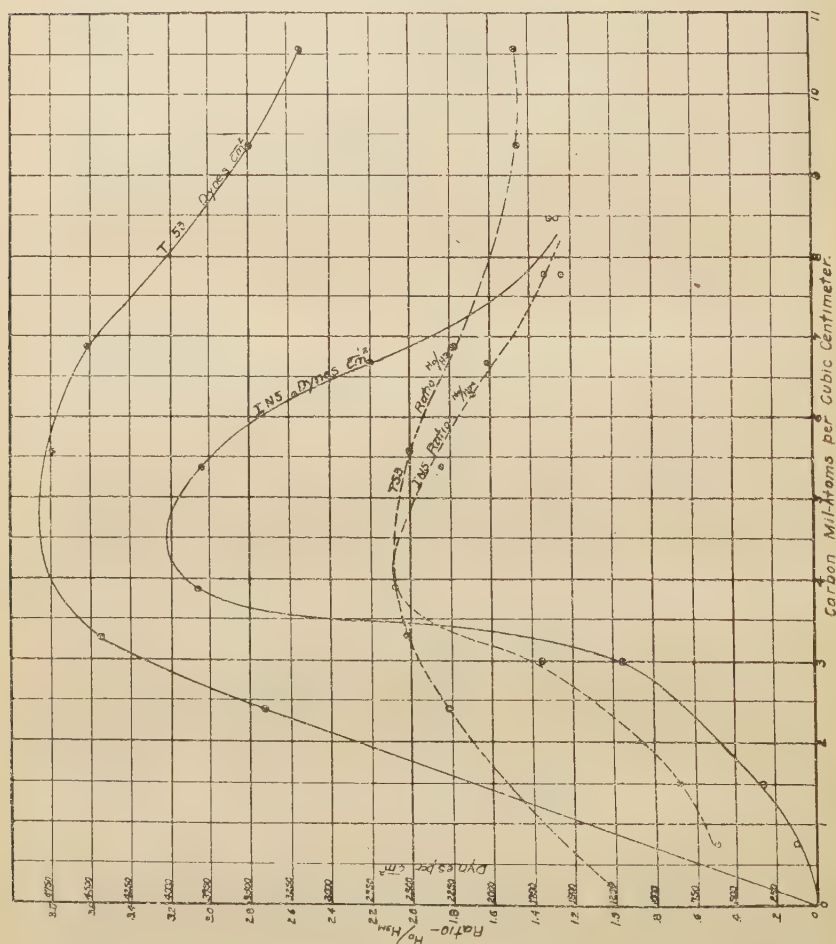


FIG. 2.

### SUMMARY.

1. Two series of steel bars have been prepared, the bars of each series differing only in carbon content. The pure iron-carbon series contains from zero to 1.30 per cent. carbon. The

chromium steel, containing 2.23 per cent. chromium, contains from 0.04 to 1.62 per cent. carbon. This latter is the first series of the kind to be prepared.

2. One or more of three principles were applied in preparing the series : carburisation with suitable carburising mixture under controlled temperature and time ; decarburisation with hydrogen at  $950^{\circ}\text{C}.$  ; and equilibration in still, dry hydrogen at  $950^{\circ}\text{C}.$

3. Measurements of specific resistance at  $25^{\circ}\text{C}.$  were made on both series in the annealed condition and after quenching in oil from  $900^{\circ}\text{C}.$

4. Experimental evidence is given in support of a new hypothesis, which offers a plausible explanation of the mechanism of remanent magnetism.





## Iron and Steel Institute.

### EXAMINATION OF IRON FROM KONARAK.

BY J. NEWTON FRIEND, D.Sc., AND W. E. THORNEYCROFT, B.Sc.  
(BIRMINGHAM).

IN 1912 a detailed description was given by Mr. Graves of the iron beams from the black pagoda at Konarak in the Province of Bihar and Orissa. The temple lies some twenty miles from Puri, which is 311 miles from Calcutta, and in all probability dates back to the thirteenth century. The beams had been used as supports under the lintels of the doorways and to assist in the corbelling-in of the roof. Through the kindness of Mr. Graves and of the Secretary of the Iron and Steel Institute, Mr. George C. Lloyd, we have been able to examine a specimen of the metal.

#### (a) MICROSCOPIC EXAMINATION.

The specimen, measuring 2.5 cm.  $\times$  2.4 cm., was polished for microscopic examination, and etched in a saturated solution of picric acid in alcohol. Some difficulty was encountered at first in obtaining a satisfactory section, due largely to the slag inclusions in the "cracks." In the centre of the specimen were a number of holes, varying in size and depth; from these radiated "cracks," as shown in the accompanying sketch (Fig. 1, Plate XIII.). The photograph (Fig. 2, Plate XIII.), taken at a magnification of 50 diameters, shows a portion of the specimen near one of the cracks. The crack itself is seen as a black mass; in contact with it is a light border of ferrite, the grain boundaries being faintly discernible; while this in turn passes into a mixture of pearlite and ferrite. Portions of the specimen away from the cracks showed a fairly uniform structure typical of mild steel containing rather less than 0.15 per cent. carbon; while portions of the specimen bordered by the holes and cracks showed no signs of pearlite. The examination lends support to the statement by Graves that "the method of manufacture was by welding up small blooms," and apparently decarburisation took place during the operation of welding.

The specimen was found to be very soft, the Brinell hardness

number (using a load of 500 kilogrammes) having a mean value of 72—a value less than half of that (namely, 188) found by Sir Robert Hadfield for the Delhi metal.

A test was made with the Shore scleroscope in order to determine any variations in hardness. Using the magnifier hammer the hardness number varied from 31 to 28 in different parts of the specimen.

### (b) CHEMICAL ANALYSIS.

Owing to the irregularity of the metal, to which attention has already been directed, it was a little difficult to choose a thoroughly representative portion for analysis. The piece ultimately chosen was as free as possible from attached slag, and its composition is given in the accompanying table, together with that of a sample

TABLE I.—*Analyses of Indian and other Irons.*

	Konarak Iron. c. A.D. 1250.	Modern Mild Steel.	Delhi Pillar. c. A.D. 300.	Dhar Pillar. c. A.D. 320.	Ceylonese (Sigiriya). c. A.D. 450.
Carbon . . .	0.110	0.080	0.080	0.02	traces
Silicon . . .	0.100	0.170	0.046	...	0.26
Sulphur . . .	0.024	0.025	0.006	...	0.022
Phosphorus . . .	0.015	0.040	0.114	0.28	0.34
Manganese . . .	trace	0.36	nil	...	traces
Copper . . .	...	...	...	...	0.012
Hardness (Brinell) .	72	...	188	...	...

of modern mild steel; analyses of specimens from the famous Delhi and Dhar pillars and from Sigiriya in Ceylon, as given by Sir Robert Hadfield,<sup>1</sup> are also quoted. The low phosphorus content is noteworthy, in view of the high percentage present in the other Indian and Ceylonese specimens. The silicon is higher than in the Delhi pillar, but this may well be due to slag or other siliceous inclusion. The carbon is a little high. On the whole, however, the composition indicates that the source of the metal was very pure. The sulphur content resembles that of the Ceylonese metal.

<sup>1</sup> This *Journal*, 1912, No. I. pp. 134 and 171 (insertion).

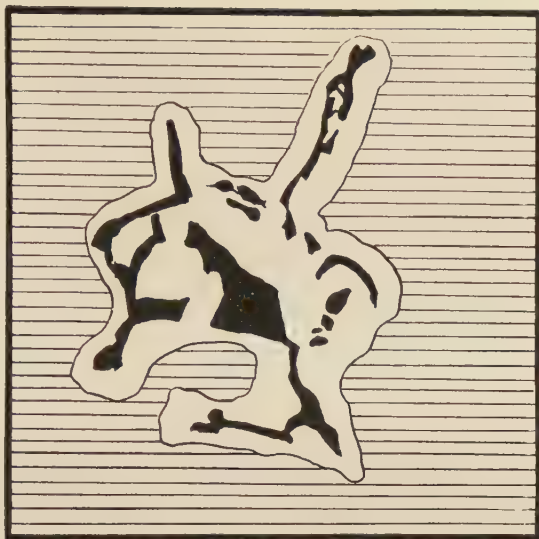


FIG. 1.—A Macrosection of Konarak Iron.  $\times 3$ .  
Black : holes and cracks. White : ferrite. Shaded : ferrite and pearlite.

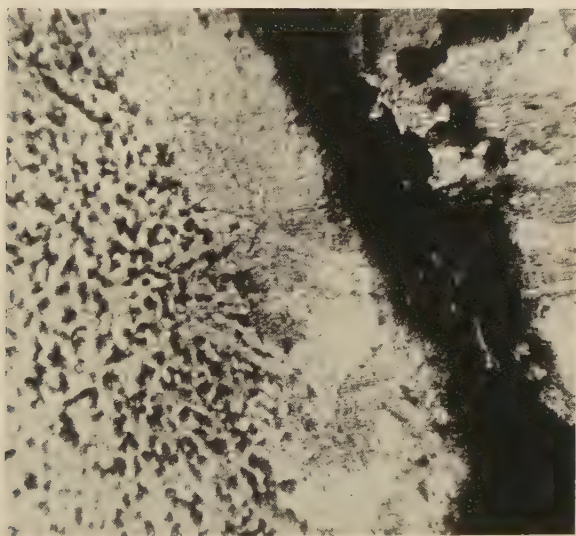


FIG. 2.—Konarak Iron.  $\times 50$ .





## (c) CORROSION TESTS.

The metal was cut into a small rectangular block and exposed, along with a similar block of modern mild steel (specimen 2, Table I.), to the corrosive influence of alternate wet and dry (tap water) for one year. It was then removed, cleaned and weighed, the loss in weight being taken as a measure of corrosion.

The specimens were then exposed for one year to action of artificial sea-water, made by dissolving the requisite quantity of Cheshire rock-salt in tap water. The tank containing the specimens held about 1 ton of the sea-water.

The results were as follows :

TABLE II.

Konarak metal,  $0.655 \times 0.968 \times 1.015$  cubic inches.  
Mild steel standard,  $0.650 \times 0.985 \times 1.025$  „ „

Metal.	Treatment (One Year each).	Loss in Weight. Grammes.	Areas Exposed. Square Inches.	Relative Corrosion per Unit Area.
Konarak Steel . . .	{ Alternate wet and dry }	2.6747 3.0438	3.845 3.909	89.3 100.0
Konarak Steel . . .	Sea-water ...	0.4250 0.5740	3.845 3.909	75.3 100.0

It is interesting to note that in both sets of experiments the ancient metal has proved appreciably more resistant to corrosion than the modern mild steel. It is not altogether easy to understand why this should be the case, particularly in view of the lack of homogeneity depicted in its microstructure, a feature that is usually regarded as conducive to corrosion. It is certainly very curious that, in most cases where ancient irons have been tested, their resistance towards corrosion has been very marked.

In conclusion, the authors desire to thank the Government Grant Committee of the Royal Society for a grant which has enabled them to make this micrographic study.



## Iron and Steel Institute.

### A NOTE ON THE EFFECT OF GRAIN-SIZE ON THE EXTENSION AT THE YIELD POINT IN ARMCO IRON.

By R. ARROWSMITH, B.MET. (NORTHWICH).

In a recent paper Thompson and Millington<sup>1</sup> have suggested that in a single crystal, or a coarse aggregate of iron, movement, when the elastic limit is passed, takes place on the rhombic dodecahedral plane. If this occurs there is no reason to expect a yield point, the stress-strain curve probably being similar to that in a close-packed non-ferrous metal such as copper. In a fine aggregate the effect of the numerous boundaries will, it is suggested, inhibit dodecahedral movement and result in deformation taking place upon a cube face. If the latter type of movement occurs the well-known yield point of iron is expected.

At the time that the paper was read no very satisfactory experimental evidence was available from which to check these conclusions, and it was for that reason that the present short investigation was undertaken. As will be seen, the results amply confirm the expectation. The coarsest aggregate shows no yield point at all, and the longest yield range is given by the sample with the smallest crystals. The results, therefore, provide experimental confirmation of this part of the conclusion reached by the authors named.

#### MATERIAL AND INSTRUMENTS USED.

The material used for the research work was Armco iron in the form of cold-drawn wire, 0.168 inch diameter. Test-pieces 19 inches in length were used, the central 2 inches of each piece being ground down, after heat treatment, to 0.125 inch diameter.

The extensometer used for measuring the extension of the test-piece was a slightly modified type of the Unwin appliance. One division of the micrometer head represented 0.001 inch,

<sup>1</sup> *Journal of the Iron and Steel Institute*, 1924, No. I.

while by estimation it was possible to read to 0.0001 inch. An Avery 6000-lbs. vertical compound lever testing machine was used in breaking the test-pieces.

#### HEAT TREATMENT OF SPECIMENS.

This consisted in annealing the specimens in an electrically heated resistance furnace, in order to obtain the ferrite grains of the desired size. No attempt was made to obtain an identical grain-size throughout the whole length of the specimen, the central 2 inches of the piece which was subsequently to be ground down and measured only being considered.

Three specimens, A, B, and C, were annealed at different temperatures, and the grain-sizes and length of yield resulting are given in the following table:

	Annealing Temperature.	No. of Grains per Sq. Mm.	Per Cent. Increase of Length at Yield Point.
A	1056° C. for 7 hours . . .	87	nil
B	920° C. for 1½ hours . . .	220	0.81
C	770° C. for 19 hours . . .	1000	1.57

#### ESTIMATION OF GRAIN-SIZE.

This was done by projecting an image of the etched specimen on the ground-glass screen of the Zeiss photomicrographic apparatus. A square was drawn on the screen and, a typical field having been selected, the number of grains falling within the square were counted and ticked off with a pencil, grains falling over the edge of the square being counted as a half. The magnification of the apparatus and the size of the square being known, it was a simple matter to calculate the number of grains in a square millimetre of the specimen.

#### BREAKING THE TEST-PIECES.

A load of 100 lbs. was applied to each specimen before any extension was measured. The load was then applied gradually,

taking care to keep the beam balanced all the time, and the extension measured. The results obtained are plotted in Fig. 1.

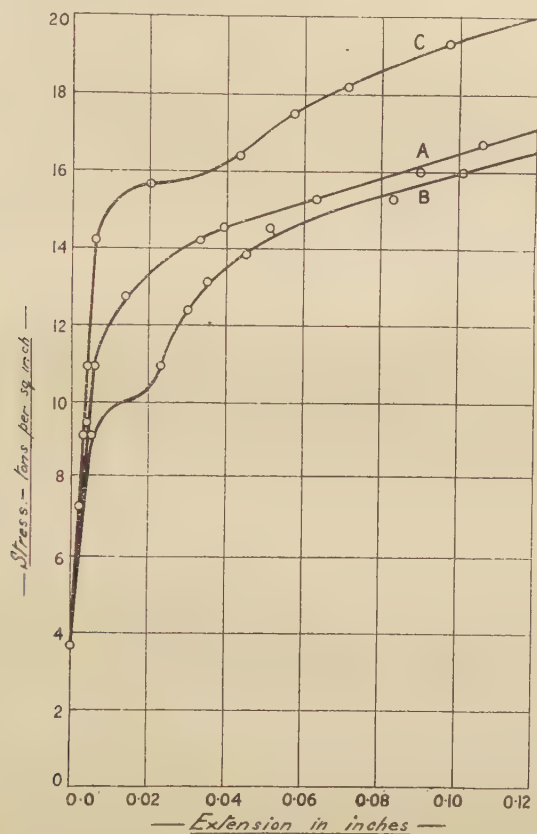


FIG. 1.

This work was carried out in the Metallurgical Laboratories of the Victoria University of Manchester.



## OBITUARY.

EDWARD T. AGIUS died on September 21, 1924. He was principal of the firm of E. T. Agius Ltd., coal exporters, of Lime Street, London, which he founded fifty-five years ago. He was until recently a member of Lloyd's, and he had been a member of the Baltic Exchange since 1869, being the oldest active member of that Institution. He had a large connection on the Continent, where both his industrial and social interests were extensive, and in 1912 was appointed a Chamberlain of the Court of the Vatican. He was elected a member of the Iron and Steel Institute in 1895.

Sir GEORGE BEILBY, F.R.S., died on July 31, 1924, in his seventy-fourth year. He was the son of Dr. G. T. Beilby, a well-known medical practitioner in Edinburgh, and was educated privately and at Edinburgh University. In 1869 he entered the services of the Oakbank Oil Company, and thereby began a lengthy association with the Scottish oil shale industry, in the course of which he introduced several important improvements in the distillation process, chief among which was a method for recovering ammonia from the spent retort material. It is of interest to note that the use of steam in gas production for the purpose of recovering the nitrogen of the coal as ammonia was first proposed by Beilby, who practised it on an industrial scale at the Oakbank Oil Works. He was no less successful in the other industrial enterprises with which he was associated, notably the Castner Kellner Alkali Company and the Cassel Cyanide Company. It was while engaged with the last-named company that his important researches on low-temperature carbonisation of bituminous coal were begun. His private industrial enterprises and technical work did not, however, exclude other interests. He was a prominent supporter of the Glasgow and West of Scotland Technical College, of which he was a governor up to his death, and Chairman for many years, during which it became in 1912 the Royal Technical College, and in 1913 was affiliated to the University of Glasgow. In 1900, when the National Physical Laboratory was instituted, he was a member of the first Committee. His work on fuel came prominently before the public when in 1903 he reported at some length to the Royal Commission on Coal Supplies, with considered and valuable estimates of the consumption of coal in the several services in which it is used, and of the order of magnitude of the economies that seemed possible in each by the adoption of improved methods. He was also a member of the Royal Commission on Fuel and Engines for the Navy, 1912-13. The outbreak of the European War directed attention to the findings of that Commission in the matter of developing

a native source of oil supply by the adoption of low-temperature carbonisation of coal. His help in war matters was sought when it had been decided to reply to the German gas attacks in 1915. He gave it immediately and ungrudgingly. All the wide manufacturing knowledge that he possessed or that was among the trade secrets of his companies was placed unreservedly at the disposal of the Government. He became a member of the War Office Committee then formed to devise and test materials for offensive chemical warfare. On the formation of the Ministry of Munitions this branch of research was transferred to the new Ministry. Throughout these years he gave his whole time to work for the Government, mainly in the Trench Warfare Department and its successor, the Chemical Warfare Department. In 1915, when the Privy Council set up its Committee for Scientific and Industrial Research, he was asked to serve as one of its first members. He subsequently accepted the Government's invitation to become Chairman and Director of the Fuel Research Board. The institution of the Board was followed rapidly by a decision to erect the Fuel Research Station, in every detail of the design of which he was personally concerned. Outside his work on fuel, he devoted close attention to certain aspects of metallurgy, contributing notably to the theory of flow of metals. He investigated the effects of various forms of mechanical work on the crystalline structure of metals—for example, the disturbances which occur in the processes of polishing and burnishing. He made an experimental study of a number of solids in various states of aggregation. His researches in this field, which were ingeniously planned and most accurately carried out, were of an entirely novel kind. He gave an account of this work in the May Lecture which he delivered to the Institute of Metals in 1911. In his book, "The Aggregation and Flow of Solids" (1921), he published collected records of his work on this subject, including his more recent investigations, based on most careful work and on observations repeated time and again. These and the theory of the hard and soft states of metals which he put forward in 1911 had a profound influence for several years on the development of metallography, and gave rise to a variety of researches designed to test the range of application of his theory. In view of recent researches on the constitution of matter it is difficult to judge the precise form of the theory which will ultimately be accepted, but there can be no two opinions as to the magnitude of the service he rendered to the elucidation of the changes produced in metal crystals by mechanical work of all kinds.

He received the honour of knighthood in 1916. He was a Doctor of Laws of Glasgow and Birmingham, and a Doctor of Science of Durham. He was elected a member of the Iron and Steel Institute in 1900.

CHRISTOPHER ROBERT CORNING, of New York, died at Châtel-Guyon, France, on July 2, 1924, at the age of sixty-five. He was one  
1924—ii.

of the ablest mining engineers and geologists in America. He was educated at Zurich and at the Bergakademie at Freiberg, where he graduated in 1883. He continued his studies at Heidelberg until 1886, when he returned to America. He served in several mining districts of America, and in 1897 he joined the firm of Olcott, Corning and Peele, consulting mining engineers. During the last ten years he maintained his office in New York as a consulting engineer. He was one of the organisers of the Mining and Metallurgical Society of America, and served as a member of the John Fritz Medal Board of Award. He was elected a member of the Iron and Steel Institute in 1913.


JOHN HENRY CREMER died at Spartanburg, South Carolina, on July 20, 1924, at the age of seventy-eight. He was born at Batavia, and was of French Huguenot descent. He went to America when a young man, after having received his education in Paris and Liège. For a time he was associated with Andrew Carnegie in the management of blast-furnaces. Subsequently he established himself in Cleveland, Ohio, as an analytical chemist, specialising in iron ore analysis. In this work he was associated for a number of years with G. A. Bicknell, and was co-author with the latter of the "Chemical and Metallurgical Handbook," published in 1898. He was elected a member of the Iron and Steel Institute in 1886.

WALTER CROOKE died on June 30, 1924, at his residence, Fern Villa, Oswald Road, Scunthorpe, at the age of eighty-four years. He was for many years engineer of the Millom and Askham Ironworks, and while there patented the Massicks and Crooke hot-blast stove, which he described in a paper read before the Institute in 1890. He took up his residence at Frodingham in 1909, and with the assistance of his second son, Mr. Arthur Crooke, general manager of the Frodingham and Appleby Works, he introduced the Crooke revolving top for blast-furnaces. He was elected a member of the Iron and Steel Institute in 1883.

GEORGE LAUDER died at Greenwich, Connecticut, on August 24, 1924, at the age of eighty-seven. He was educated at the Glasgow University. In 1892 he became a director of the Carnegie Steel Company, which had just been formed. He was associated with Andrew Carnegie for thirty years. He retired from the steel business in 1901, when the Carnegie Steel Company was acquired in connection with the formation of the United States Steel Corporation. He was elected a member of the Iron and Steel Institute in 1888.

THOMAS COMMERFORD MARTIN died at Pittsfield, Massachusetts, on May 17, 1924. He was born in London in 1856 and was educated at Gravesend. He was associated with Thomas A. Edison in electrical research from 1877 to 1897, and had been editor of the *Electrical World*

from 1883 to 1909. He had lectured on engineering subjects in England and France, and in 1907 was decorated Officer of Public Instruction by the French Government. He was a Past-President of the American Institute of Electrical Engineers and of the New York Electrical Society. He was also a member of the Engineering College, George Washington University, and of numerous scientific clubs and societies. He was a member of the committee organised by the American engineering societies to expend the \$1,500,000 gift of Andrew Carnegie for the erection of a United Engineering Societies Building and the Engineers' Club in New York. He was a frequent contributor to scientific and trade journals, and was author of books on research and invention. He was elected a life member of the Iron and Steel Institute in 1905.

 EDGAR WINDSOR RICHARDS died in London on August 5, 1924. He was born in 1863, and was the son of the late Edward Windsor Richards, Past-President. He was educated at Giggleswick and Bishop Auckland, and received his training in the steel industry at Messrs. Bolckow Vaughan's Works in Middlesbrough. He afterwards went to America, and filled positions with the Carnegie Steel Company and the Scranton Steel Company, in charge of their steel department and mills. On his return to this country he was appointed manager of the steel-making department at the Barrow Works, which position he left when he was appointed general manager of the works of the Glengarnock Iron and Steel Company, Ltd. He held this position for twenty-three years, during which time the works were entirely remodelled. Subsequently he resided in London, and was chairman and director of Edgar Windsor Richards & Company, consulting engineers, of Long Acre. He was a Vice-President of the West of Scotland Iron and Steel Institute, and was elected a member of the Iron and Steel Institute in 1892.

Comm. Ing. GIULIO VITALI died at his residence in Turin on April 4, 1924, at the age of fifty-two, having been born at Bologna in 1873. As a young man he spent some years studying the practical metallurgy of iron and steel at works in France, Belgium, and Germany, and on his return to Italy he joined the staff of the Ligure Metallurgico at Sestri, and was shortly after made general manager of the works. He occupied subsequently similar positions at Savona and at Piombino. In 1910 he surrendered his position as deputy chairman of the Piombino Company and established himself in private consultative practice, but in 1912, at the urgent solicitation of Comm. Gatta, the managing director of the Piemontesi Company, he joined the board and took over the management of the Turin Works of the Company. In 1917, when these works were absorbed by the F.I.A.T. Company, Mr. Vitali became general manager of the entire iron and steel plant of that undertaking. He was thus identified in a striking manner with the iron and steel industry of his native country all his life, and much of the progress and great development of the important modern plant of the

F.I.A.T. Company at Turin was due to his foresight and to his great administrative and organising powers.

Although suffering at the time from a malady which had already severely sapped his powers, he threw himself with enthusiasm into the task of organising the arrangements made to receive and entertain the members of the Iron and Steel Institute who visited Italy at the autumn meeting of 1923, and was present on the occasion of their visit to the F.I.A.T. metallurgical plant in Turin, and contributed by his personal influence and interest in no small measure to the success with which the visit to Turin was attended. He was elected a member of the Iron and Steel Institute in 1907.



## SECTION II.

*NOTES ON THE  
PROGRESS OF THE HOME AND FOREIGN  
IRON AND STEEL INDUSTRIES.*

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In the preparation of these Notes the Editor has been assisted by L. P. SIDNEY,  
Assistant Secretary, and others.

# IRON ORES

## AND OTHER METALLIFEROUS ORES USED IN THE IRON AND STEEL INDUSTRY.

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### I.—GEOGRAPHICAL DISTRIBUTION OF ORES.

(Arranged in alphabetical order under Countries.)

**Australia.**—*Industrial Minerals* (Queensland Geological Survey, 1920–21, Publication 268). This publication is divided into nine parts, each part containing a review of the occurrence, treatment, uses, values, and production of certain industrial minerals in Queensland. Molybdenite is dealt with in Part 4, nickel in Part 6, graphite in Part 7, manganese in Part 8, and arsenic in Part 9.

**British Empire.**—*Mineral Resources of the British Empire* (Mining Journal, Special Empire Mining Number, June 21, 1924, vol. 145, 84 pp.). A review is published of the mineral resources and mining activities in all parts of the British Empire.

**Bulgaria.**—D. A. Wray, *Mineral Resources of Bulgaria* (Mining Magazine, 1924, vol. 30, p. 73). The iron ore deposits of Bulgaria are of small extent, but they contain ore of good quality, and are probably sufficient to supply local needs of iron and steel for many years. In Eastern Rumelia, south of Yamboli, a magnetite ore deposit occurs in the form of lenticular masses in syenite. The principal part of this deposit is known as the Blagovest concession. Another magnetite ore deposit is found at Samakoff, in the upper Isker valley. Similar, but smaller deposits of the same kind are found on the northern slopes of Stara Planina, in the neighbourhood of Kustendil, at Kavakli, and at several places in the Rila and Rhodope mountains. Hematite ore deposits are found near Kreminovsi and Bresnik. The Kreminovsi ore is stated to have an iron content as high as 60 per cent. The Bresnik deposit is similar in character, with a varied iron content of 52.3 per cent., and an estimated ore tonnage exceeding one million.

Magnetite sands with a high iron content, and low in phosphorus and silica, are found in the coastal district of Bourgas. Deposits of manganese ore, while not yielding ore of the highest grade, are of some importance for a local iron and steel industry. The deposits occur in three districts, near Sofia, Yamboli, and Varna respectively. Chromite in small quantities occurs in numerous localities, and between Sotir and Ferdinand in north-west Bulgaria, large masses have been found in the serpentine.

**Canada.**—J. G. Morrow, *Report of Sub-Committee on Iron Ore* (Honorary Advisory Council of Scientific and Industrial Research, Canada, Report No. 14, 1924). This report discusses the nature of the Canadian iron ore deposits and the economic difficulties. Canadian ores must be beneficiated to compete with the ores of Michigan, Wisconsin, and Minnesota. The sintering process is preferable to the briquetting process, particularly as regards reduction in the blast-furnace. Under present conditions electric smelting of iron ore and smelting of titaniferous iron ore are impracticable.

E. L. Bruce, *Iron Ore in the Lake St. Joseph District, Ontario* (Thirty-first Annual Report of the Ontario Bureau of Mines, 1922, Part 8). Iron-bearing rocks of economic interest occur on islands in Lake St. Joseph, and below some parts of the lake itself. The ore bodies are lenticular, the largest appearing to be continuous for about five miles. The iron minerals are magnetite and specular hæmatite—each occurs in fine grains intimately mixed with silica. Analyses of seven samples showed an iron content ranging from 32.60 to 37.92 per cent., no sulphur, and only a trace of titanium. Determinations of phosphorus in three samples gave 0.1209, 0.1564, and 0.203 per cent. respectively. Magnetic concentration tests showed that by crushing the ore to pass a 200-mesh screen a concentrate containing nearly 60 per cent. of iron could be obtained, but that not more than 30 per cent. of the total iron was recovered.

A. H. A. Robinson, *The Mineral Industries of Canada* (Canada Department of Mines, Ottawa, 1924). This booklet has been revised for distribution at the British Empire Exhibition. It presents in popular form a brief sketch of the more important economic minerals of Canada.

**China.**—F. R. Tegengren, *The Iron Ores and Iron Industry of China* (Memoirs of the Geological Survey of China, Series A, No. 2, Part 1, Oct. 1921; Part 2, Dec. 1923). Part 1 of this memoir is devoted to a description of the individual iron ore deposits of Chihli, Manchuria, Shantung, Shansi, and Honan. Part 2 includes a description of the deposits of Hupei, Anhui, Kiangsu, Chekiang, Fukien, Kuangtung and Kuangsi, Kiangsi, Hunan, Kueichou, Ssuchuan, and Yunnan. A general survey and an account of the primitive native iron industry are given, also a review of the modern industry which includes

descriptions of the Han-Yeh-Ping works, the blast-furnace of the Yangtze Engineering Works, the Lung-Yen Ironworks, the Pen-Ch'i-Hu Ironworks, the An-Shan Ironworks, and the P'u-Tung Iron and Steel Works. The general position of the industry is reviewed, and particulars are given of the costs of production per ton of pig iron. Tables are also given showing the production and consumption of iron and steel in China. In view of the intimate connection and interdependence of the iron industrial possibilities of China and those of the Far East and the Pacific regions, a brief summary of the available information relating to the iron industry of Pacific Asia, America, and Australia is incorporated in the memoir. The memoir concludes with a list of references to the literature on iron ore and iron in China.

Raby, *The Iron Ore Resources of Northern China* (Bulletin Économique de l'Indo-Chine, October 1923, p. 444; Bulletin of the Imperial Institute, 1924, vol. 22, No. 1, pp. 90-92). The author deals with the iron ore resources of Manchuria and the Chihli and Shantung provinces in Northern China. The deposits contain some rich iron ore, but the larger proportion, while constituting useful ores, are only of moderate grade. Generally, the ores are low in phosphorus and sulphur, and apparently are not titaniferous. The principal deposits are associated with Archæan rocks, and the ore minerals are magnetite and hæmatite. The Manchurian deposits are the most extensive, and are found in four districts. The principal district is Anshan, traversed by the Dairen-Mukden Railway. The ore reserves have been estimated at 400 million tons, with an iron content of 31 to 55 per cent., and 2 million tons of richer ore, with an iron content of 48 to 65 per cent. The Kung-Chang-Ling deposits are 20 miles from the Antung-Mukden Railway. The ore reserves are estimated at 268 million tons, with an iron content of 29 to 40 per cent., and 2,300,000 tons of rich ore containing 60 to 68 per cent. of iron. The ore reserves of Miao-Erh-Kou deposit amount to 70 million tons of ore containing 33 to 38 per cent. of iron and 2 million tons with an iron content of 59 to 70 per cent. The Kuo-Ti-Shan deposits are relatively small and not of high grade. The ore minerals are magnetite and hæmatite. In Chihli Province the iron ore deposits are estimated to contain 57,800,000 tons, with an iron content of 57 to 58 per cent. At Hsin-Yao are iron ore deposits about forty-two miles from Hsuan-Hua station on the Pekin-Kalgan Railway. These are estimated to contain 17,800,000 tons of ore, with an iron content of 48 to 59 per cent. Another deposit at Yen-Tung-Shan is about six miles from Hsuan-Hua station. It contains an estimated quantity of 12,900,000 tons of ore, with 32 to 58 per cent. of iron occurring in argillaceous schists and sands of pre-Cambrian age. In the basin of Luan-Hsien is a group of iron ore deposits of low grade, with an iron content from 25 to 40 per cent. The ore reserves are estimated at 31 million tons. In the Shansi Province are numerous small deposits of iron ore, rather high in phosphorus, but suitable for the production of steel by the basic process. Shantung Province

contains one iron ore deposit at Chin-Ling-Chen or Tieh-Shan, near the Tsinan-Tsingtao Railway, and about 120 miles from the port of Tsingtao. The estimated ore reserves are 13 million tons of hæmatite and magnetite ore with an iron content of 33 to 66 per cent. This deposit was discovered by Germans in 1899 and exploited by them to supply a blast-furnace at Kiaochow. The Japanese took over the deposit in 1914 and exported ore from it to Japan.

M. Brucher, *The Metalliferous Ores and Other Useful Minerals of China* (Glückauf, August 30, September 6, 13, 20, 1924, vol. 60, pp. 759-765, 789-795, 811-815, 840-848). A general review of the mineral resources of China, other than coal and iron.

Wong Wen-Hao, *The Mineral Resources of China* (Memoirs of the Geological Survey of China, Series B, No. 1, July 1919). This memoir, which is in the Chinese language, describes the resources of metals and non-metals, with the exception of coal.

V. K. Ting, *The Manganese Deposits of Hsi Hu Hs'un, Chang Ping Hsien, Chihli* (Bulletin of the Geological Survey of China, October 1922, No. 4, pp. 91-96).

**France.**—L. Cayeux. *Magnetic Iron Ore in the Grey Seams of Hayange* (Revue Universelle des Mines, December 1923, vol. 19, pp. 61-68). A description of the occurrence of pockets of magnetic iron ore in the vicinity of the Hayange fault. The throw-down reaches a depth of 70 to 80 yards, and on each side of it the magnetic deposits are found. The mineralogy and petrographic characters of the ore are discussed.

**Panama.**—J. F. Sheridan, *Manganese Ore Deposits in Panama* (Iron Age, August 21, 1924, vol. 114, pp. 444-447). A survey is given of the manganese ore deposits in Panama. Manganese ore occurs in abundance on the Pequeni River and adjacent territory, and is high in manganese dioxide and metallic manganese. The deposits so far have only been mined on the surface. Mention is also made of the occurrence of manganese ore in Costa Rica. The deposits thus far discovered are all on the Nicoya Peninsula, on the Pacific coast. Most of them are of rather low grade or of small extent.

**Spain.**—Demay, *Geological, Metallurgical, and Economic Notes on the Mineral District of Carthagena* (Annales des Mines, 1924, vol. 5, pp. 137-193). It is in the upper calcareous deposits that iron ore is found. This is of high quality, and is usually in the state of a hydroxide, although carbonates are also found. The higher grade ore, which contained as much as 53 per cent. of iron, has largely been exhausted. Manganese ore is also found, the manganese percentage being in some instances fairly high (22 to 26 per cent.). The theory of the formation of these deposits is given, after which a short account is given of the early history of mining, which dates back to the time of the ancient



Romans. The modern working of these ores dates, however, only from as comparatively recently as 1842. The output in 1913 was 490,032 metric tons, which fell, however, in 1915 to less than half this amount. Production has never recovered, and the figures for 1921 were only 98,063 tons. Data are given of the cost of labour, overhead charges, and average prices. At present the mining industry is suffering from the general uncertainty which pervades so many other industries.

**Sweden.**—P. Nicou, *The Swedish State, and the Large Deposits of Exportable Phosphoric Iron Ore* (Annales des Mines, 1923, vol. 4, pp. 181–226, 255–335). A continuation of the account of the iron ore resources and the organisation of the industry in Sweden (abstracted, Journal of the Iron and Steel Institute, 1923, No. II. pp. 382–383). The legal aspects of the various concessions, and the periods for which they have been granted, together with the allocation of the tonnages which may be exported, are given. The text of the various contracts between the ore mining companies and the Government is given in full.

W. Petersson, *Deep Surveys of the Iron Ore Deposits of Kiirunavaara and Gellivare* (Jernkontorets Annaler, 1924, vol. 108, pp. 193–241). The work of surveying these extensive iron ore deposits by means of bore holes was begun in 1914, and was brought to a conclusion in 1923. Analyses of samples taken at different levels show extremely favourable results as regards the content of iron and phosphorus. At Kiirunavaara deep bore-holes were in some cases carried to a depth of 700 metres, the thickness of the ore beds passed through being from 100 to 190 metres. The iron and phosphorus ranged from 68·3 per cent. iron and 0·04 per cent. phosphorus in Grade A, to about 52·0 per cent. iron and 2·0 per cent. phosphorus in Grade G. The total reserves of ore are of enormous extent.

P. Geijer, *The Geological Conditions of Kiirunavaara as shown by Deep Borings* (Jernkontorets Annaler, 1924, vol. 108, pp. 243–254).

**United States.**—A. F. Rogers, *Kempite, a New Manganese Mineral from California* (American Journal of Science, August 1924, vol. 8, pp. 145–150). The new mineral was found by the author in a huge boulder of manganese ore in Alum Rock Park, near San José, California. The minerals forming the boulder also include tephroite, hausmannite, rhodochrosite, barite, pyrochroite, psilomane, ganophyllite, and a small amount of alabandite. The kempite was found as minute enehedral crystals in cavities associated with pyrochroite crystals, and in small patches sporadically distributed through impure hausmannite. It is very rare and irregularly distributed. In colour it is emerald green with a specific gravity of about 2·94. The composition was found to be :

Mn.	Cl.	H <sub>2</sub> O.	O (by difference).
50·59	16·41	11·60	21·40

This corresponds with the empirical formula  $Mn_4Cl_2O_6 \cdot 3H_2O$ . Kempite is the only known manganese oxychloride. Rhodochrosite often surrounds kempite and is apparently an alteration product of it.

**Origin of Ore.**—F. Behrend, *The Formation of Iron and Manganese from their Hydroxide Salt Solutions in Surface Deposits* (Zeitschrift für praktische Geologie, July, August 1924, vol. 32, pp. 81–89, 102–108). The examination of lacustrine and bog ores has led the author to the belief that where these consist of iron and manganese ores they have been formed by precipitation from hydroxide solutions containing these minerals as salts. Evidence in support of this theory is presented.

K. Hummel, *Origin of the Manganiferous Iron Ores in the Limestone of the Spessart and Odenwald* (Glückauf, August 30, 1924, vol. 60, pp. 765–768). The view is maintained that these ores were formed as metasomatic deposits from hot springs percolating upwards. This theory is supported by the fact that the ores are associated with spathic siderite and barytes. The beds are of Tertiary Age. At the surface the ore has become enriched by weathering, and the deposits may be regarded as a potential reserve. They run to considerable depth, but except at the outcrop they are too lean to have much economic value.

**Valuation of Ore Properties.**—P. L. Burthe, *Note on the Valuation of a Metalliferous Mine* (Revue Universelle des Mines, May 1, 1924, vol. 2, pp. 138–158). Gives formulæ for the valuation of mineral deposits when the various factors, such as ore available and in sight, are known. A number of actual examples are worked out, including instances relating to the iron ore deposits of Kierum, and of Gellivare, wherein the whole of the factors, comprising ore estimates, purchase price, and conditions of lease, &c., are assembled, and the probable profits estimated.

## II.—PREPARATION OF ORES.

**Examination of Ores.**—E. E. Fairbanks, *Microchemical Determination of Ores* (U.S. Bureau of Mines, Advance Report, 1924, Serial 2613). Microscopic methods have proved of value in the study of low-grade ores. The minerals are often so finely disseminated and intermixed that identification, even by microscopic methods, is difficult; the author has accordingly devised a small boring appliance for obtaining drillings, in order to overcome the difficulty of getting a small amount of uncontaminated material from a disseminated mineral. Such drillings facilitate the identification of the various minerals encountered in the study of low-grade potential ores.

**Leaching of Iron Ore.**—A. J. Moxham, *Purifying Iron Ore by Chemical Methods* (Iron Age, June 5, 1924, vol. 113, pp. 1637–1639). Particulars are given of experiments on the purification of iron ore by leaching. A small plant has been built to work the Delaware greensands, one of the largest deposits of low-grade iron ore in the United States. The greensand is leached with acid, with subsequent washing for the separation of iron, potash, and alumina.

**Ore Dressing.**—A. Bibolini, *Note on the Electrostatic Separation of Minerals as Applied in a New Electrical Sifter* (Revue Universelle des Mines, March 1, 1924, vol. 1, pp. 290–318). A detailed account of the Bibolini-Riboni electrostatic separator, preceded by a short summary of the principles involved in electrostatic separation generally. The theory of the new separator is discussed in full, with formulæ and diagrams, and its practical application is likewise described and illustrated.

## REFRACTORY MATERIALS.

**Quartzite.**—D. A. Hasebrink, *The Tertiary Quartzite Deposits, with Special Reference to the Quartzite Occurrences on the Middle Rhine* (Stahl und Eisen, August 21, 1924, vol. 44, pp. 1018–1022). A general description is given of the occurrences of tertiary quartzite in the Siebengebirge and Westerwald, its origin and chemical composition.

**Kaolin.**—*The Kaolin Deposits of Furtei, Sardinia* (Chemical Age, China Clay Trade Review Section, September 20, 1924, vol. 11, pp. 15–16). In the general description of the geology and occurrence of kaolin in Sardinia, reference is made to the use of certain qualities as refractory materials. The deposits in question lie in the volcanic region in the vale of Ria Sa Perdala, where extensive workings have been opened out. Hitherto there have only been industrial analyses of the kaolin from these pits, made with the raw material. Some, however, made by Professor F. Giolitti, for the Ansaldo Co., who utilise large quantities of Furtei kaolin to manufacture refractory materials for the furnaces of steel works, are not without scientific interest. According to these analyses, the kaolin from the various pits is practically free from alkali, lime, and magnesia. Iron oxide, in the form of ferric oxide in the calcined clay, is never more than 1.85 per cent., and usually only exists in traces; silica, always in the calcined clay, varies from 57 to 68 per cent.; alumina, 30 to 43 per cent. The loss at red heat is 5 to 7.5 per cent. Without dwelling further on these analyses, interesting from different points of view, reserving their study until there are more complete analyses made on a different basis, it may now be concluded that, at least in most cases, decomposition of the primitive rock, presumably rich in alkali, and certainly not without perceptible percentages of lime and magnesia, was really profound. The application of kaolin of this description for the manufacture of refractory products presents many features of interest. The Furtei pits were opened up in 1917, and the output is about 10,000 metric tons per annum.

**Magnesite.**—G. Castelli, *Italian Magnesite Deposits* (Rassegna Mineraria, 1924, vol. 60, pp. 5–8). The magnesite deposits of Castiglione, Monterufoli, Island of Elba, and Querceto are described. The deposits at Querceto are the most important in Italy.

**Preparation, Properties, and Tests of Refractories.**—R. Grun, *The Transformation of Flint into Amorphous Quartz* (Stahl und Eisen,

July 24, 1924, vol. 44, pp. 883-887). Investigations have been made as to the use of flintstones as a substitute for quartzite in the manufacture of silica bricks. Flintstones were crushed to pea size and burnt at different temperatures. Up to 1300° C. no change takes place, but above that point the transformation into amorphous quartz begins and is quantitatively complete at 1400°. The change proceeds more rapidly than in other quartz rocks, and is accompanied by considerable increase in specific weight. In fact, a single burning is sufficient to bring the flint to a condition of constant volume.

W. G. Owen, *Progress in the Manufacture and Use of Clay Refractories* (Transactions of the American Society for Steel Treating, August 1924, vol. 6, pp. 125-137). It is pointed out that the life of a fire brick greatly depends upon the care exercised in furnace construction and the quality of the mortar used. Not any one grade of brick will give most efficient results in all places. The service encountered should determine the characteristics of the brick used.

C. H. Heubling, *Modern Methods of making Silica Bricks* (Tonindustrie Zeitung, 1924, vol. 48, pp. 34-37). An improved process for the manufacture of silica bricks has been introduced at the steelworks of Esch and Stein, Duisburg. To shorten the work of crushing the quartzite to uniform size in an edge runner, the quartzite receives its preparatory crushing in a specially constructed roller crusher, and is then passed through a second roller crusher, leaving the edge mill to do no more than the final grading and mixing with lime. The edge mill for this purpose can be fitted with runners of a much lighter construction.

C. E. Sims, H. Wilson, and H. C. Fisher, *Preparation of Artificial Sillimanite for Refractory Uses* (Paper read before the American Electrochemical Society, October 1924). The experimental work leading to the adoption of a furnace for the preparation of artificial sillimanite is described. Clay was found to be peculiarly difficult to melt, but could be reduced to sillimanite by elimination of the excess silica. Natural sillimanite has a different composition from the synthetic product. Artificial sillimanite containing excess silica is vitreous; that with excess alumina is stony. The latter form has excellent refractory properties as compared with silica and magnesite brick. Lime is a particularly undesirable impurity.

H. S. Houldsworth, *Some Properties of Clay-Sillimanite Mixtures* (Paper read before the Ceramic Society, September 1924). The author has studied the changes in physical and chemical properties of a clay when mixed with different proportions of sillimanite. Test samples were fired under different conditions. The results showed that the addition of sillimanite to clay decreases the drying and firing shrinkages and increases the porosity at the higher temperatures of burning. A pronounced increase in refractoriness was particularly noted as the sillimanite content increased. Sillimanite bonded with 10 per cent. of ball clay has a marked resistance to chemical attack by soda-lime glasses



and basic slag. In the discussion following the paper the superior quality of sillimanite bricks for furnace linings was emphasised.

E. L. Dupuy, *The Mechanical Properties of Refractory Products at High Temperatures* (Revue Universelle des Mines, March 1, 1924, vol. 1, pp. 323-327). If the curve, temperature-crushing-load be examined for a number of different refractories, it will be found that these range themselves into two categories. In the first, which includes silico-alumina, silica, and alumina bricks, the crushing load, after falling slightly in proportion as the temperature increases, rises suddenly in the vicinity of  $1000^{\circ}\text{C}.$ , and then falls again until fusion is complete. The second category, which comprises most of the magnesia products, and ferro-chrome, is characterised by the absence of this maximum. In some experiments where the maximum resistance to crushing was found to be in the vicinity of  $1000^{\circ}\text{C}.$  it was found that a certain amount of strength was regained during cooling, which seemed to show that some of the constituents had fused during the tests. It was thought, therefore, that the phenomena might depend upon the presence of pasty matter, and that a refractory, at that temperature, might be regarded as consisting of two substances having different properties, and resembling, somewhat, a sponge containing more fluid particles. This view was borne out by experiment, and the somewhat paradoxical result arrived at, that as an exceedingly important factor is the rate of heating, the softening point will, if the rate of heating be rapid, be accompanied by an increase of the crushing strength. To comply with practical considerations, the rate of heating, in such tests, should therefore be slow.

M. L. Hartmann and O. B. Westmont, *Physical Characteristics of Specialised Refractories* (Paper read before the American Electrochemical Society, October 1924). Thermal conductivity measurements up to  $1350^{\circ}\text{C}.$  of silicon carbide refractory materials were made, using the water calorimeter method. Data were secured on furnace walls, such as those commonly used in practice, and results are believed to be accurate to within about 1 per cent. Conductivity measurements were made on seven carborundum single walls and on eight carborundum-fireclay composite walls. The relation of the thermal conductivity to temperature, chemical composition, and porosity was investigated, as well as the magnitude of the surface and joint effects. The conductivity of carborundum refractories was found to vary with the quantity of heat energy transmitted through the wall. Tables are given showing the coefficients of thermal conductivity and heat flow through various types of walls, with a temperature of  $1500^{\circ}\text{C}.$  in the combustion chamber.

O. A. Hougen, *Selection Factors in Choosing Refractories for Industrial Plant Use* (Chemical and Metallurgical Engineering, May 12, 1924, vol. 30, pp. 737-741). The physical and chemical properties of refractory materials are tabulated, as a guide for the selection of refractories for industrial uses.

A. J. Dale, *Relation between Ordinary Refractoriness, Underload Refractoriness, and Composition, Physical and Chemical, of Refractory Material* (Gas Journal (Supplement), July 9, 1924, vol. 167, pp. 18-23). Briquettes of raw clays containing 0, 20, 40, and 60 per cent. of grog, were moulded and fired at cones 13-14. It was found that the temperature at which subsidence begins under load is independent of the grog content, but that there is a variable range of temperature between the commencement of under-load subsidence and complete failure. With one exception the temperature at which complete breakdown occurred under load was lower with bricks containing grog than with the straight clays. The greater the proportion of grog the more rapid and the greater was the subsidence.

F. J. A. Dejardin, *Pyrometric Tests of Refractory Clays* (Revue Universelle des Mines, April 1, 1924, vol. 2, pp. 49-55). Most writers on the subject of Seger cones confine themselves to theoretical considerations, and leave the practical details respecting their use undescribed. The user has therefore to proceed empirically by a method of trial and error. A more exact method of procedure is described, including detailed instructions for making and calibrating the cones. What such cones are used for will depend upon the particular industry in which they are employed, and the results themselves will vary to some extent with the specific object sought. They can be used to determine a fairly large range of properties and to control various processes.

P. Gilard, *The Reversible Thermal Dilatation of Refractory Materials* (Revue Universelle des Mines, April 15, vol. 2, pp. 83-89). A translation of the article by H. S. Houldsworth and J. W. Cobb (Journal of the American Ceramic Society, May 1923, vol. 6, pp. 643-662; *abstracted*, Journal of the Iron and Steel Institute, 1923, No. I. p. 610).

G. E. Merritt, *Application of the Interferometer to Measurements of the Thermal Dilatation of Ceramic Materials* (U.S. Bureau of Standards, 1924: Scientific Paper No. 485). An interference method and apparatus for measuring the thermal expansion of ceramic materials are described. The samples in the form of small pins 0.5 to 10.0 millimetres in length are placed between two fused quartz interferometer plates and heated in an electric furnace. The elongation of the samples is determined from the numbers of interference fringes that pass reference marks on the interferometer plate while the sample is being heated. A change in length of the sample of  $0.025\mu$  or one-millionth of an inch can be easily detected.

W. J. Rees, *True Specific Gravity and After Expansion of Lime-bonded Silica Bricks* (Paper read before the Ceramic Society, September 1924). The author describes experiments made on the connection between the true specific gravity, or powder density, and the after expansion of certain bricks. There was found to be a sufficiently close relation for practical purposes in the case of bricks of fine or medium texture. It was also concluded that the grading of the raw material

had a greater influence on the rate of quartz conversion than variations in the source or type of the raw material itself.

W. Hugill and W. J. Rees, *A Rapid Method for the Determination of True (or Powder) Specific Gravity* (Paper read before the Refractory Section of the Ceramic Society: Engineering, October 3, 1924, vol. 118, p. 482). A method is described for determining the specific gravity of crushed refractory bricks. The results indicate that accuracy to  $\pm 0.01$  can be expected from the method, provided that the crushed brick is dried.

E. E. Pressler, *Comparative Tests of Porosity and Specific Gravity on Different Types of Refractory Brick* (Journal of American Ceramic Society, June 1924, vol. 7, pp. 447-451). In order to study the relative values of porosity and specific gravity obtained by different methods comparative tests were made upon several types of refractory bricks. Apparent porosity is obtained directly by the water absorption and air expansion methods. Total porosity is calculated from the true specific gravity, and apparent specific gravity is calculated from the observed porosity values. The results show that the air expansion method affords a more accurate means of measurement of open pore space in bricks than the water absorption method. Silica and magnesite bricks were found to have no pores sealed to the air expansion effect, but a certain percentage of pore volume remained sealed to water penetration effect.

P. Desmasure, *Behaviour of Refractory Material on Heating* (Bulletin de la Fédération des Industries Chimiques de Belgique, 1924, pp. 184-193, 238-256). The author discusses the effect of the mechanical and chemical composition, and the physical state of the material on the fusibility and hot crushing strength of refractory materials.

F. R. Ennos and A. Scott, *Refractory Materials: Fireclays, Analyses and Physical Tests* (Geological Survey, Special Reports on the Mineral Resources of Great Britain, vol. 28, London, H.M. Stationery Office).

L. J. Trostel, *Notes on a Comparative Test of Quicklimes for Silica Brick Manufacture* (Journal of the American Ceramic Society, June 1924, vol. 6, pp. 452-454).

W. J. Rees, *Storage of Silica Refractories* (Paper read before the Refractory Section of the Ceramic Society: Engineering, October 3, 1924, vol. 118, pp. 481-482). Attention is drawn to the fact that the neglect to exercise care in the storage of silica bricks may cause considerable changes, particularly in the mechanical strength and spalling tendency. A batch of silica bricks which had been stored in the open for six months showed a crushing strength of 2200 lbs. per square inch, while freshly delivered bricks of the same make had a cold crushing strength of 3000 lbs. per square inch. There are definite indications that the loss in strength is in part due to a slight degradation of the bond by hydration and solution in water, as well as to the physical effect of frequent wetting and drying. Detailed results of tests are included

in the paper. Little or no distinction was observable in the behaviour of coarse and fine textured specimens, but in both cases those burned at higher temperatures were more resistant to the water attack.

W. Hugill and W. J. Rees, *The Influence of Exposure on the Chemical and Physical Properties of Certain Fireclays* (Paper read before the Ceramic Society, September 1924). Exposure to the weather removes impurities in the clay to a variable extent, depending on their chemical and physical characteristics. It improves the working properties of silicious clays, but in the case of aluminous clay, though some impurities are removed, the general properties, especially the workability, are not materially improved by exposure.

P. Gilard, *Action of Carbon Monoxide on Refractory Bricks* (Revue Universelle des Mines, December 1923, vol. 19, pp. 329-336). A summary of certain recent investigations on the subject. The disintegration of refractory bricks subject to the action of carbon monoxide is due to the swelling caused by carbon deposition within their interstices in accordance with the reaction  $2\text{CO} = \text{CO}_2 + \text{C}$  at temperatures of about  $550^\circ\text{C}$ ., particularly when iron is present to act as a catalyser. The work of Nesbitt and Bell is discussed, together with that of O'Hara and Darby, so far as blast-furnace bricks are concerned, and the relative behaviour of silica brick, magnesia brick, and carborundum are compared. The latter is not disintegrated in these conditions, nor is chrome brick, because of the very small amount of free iron oxide present.

M. Hersey and E. Britzler, *Determination of Thermal Conductivity of Refractories* (Journal of Washington Academy of Sciences, 1924, vol. 14, p. 147). Calculations are given for determining the thermal conductivity of refractories with special reference to Georgia fire-bricks.

F. C. Nonamaker, *Technology of Zirconium and its Compounds* (Chemical and Metallurgical Engineering, July 28, 1924, vol. 31, pp. 151-155). The chemical behaviour of zirconium, its separation and purification, technical applications, the use of zirconia as a refractory, and application of other zirconium compounds are dealt with. The oxide has a melting point of about  $2900^\circ\text{C}$ . and is an excellent material for furnace linings and crucibles. The most extensive use of zirconia as a refractory is probably its employment in the form of crude zirkite, either as bricks or a mortar for blast-furnace linings.

W. J. Rees, *Alumina-Silica Minerals in Firebricks* (Paper read before the Ceramic Society, September 1924). Five different firebricks were examined as received, and subsequently after refiring at high temperatures. By treating small samples with pure hydrofluoric acid the free silica was removed and the residual minerals were analysed. The composition of the insoluble portions in all cases approximated more or less closely to that of the mineral mullite, corresponding to the formula  $3\text{Al}_2\text{O}_3, 2\text{SiO}_2$ .



**Heat Transmission of Furnace Walls.**—*Influence of the Rate of Transmission of the Heat of a Wall to a Fluid* (Chaleur et Industrie, January 1924, vol. 5, pp. 38–40). This is a summary and commentary on the controversy between H. Preussler (Stahl und Eisen, 1921, vol. 41, p. 827) and Nusselt (Stahl und Eisen, 1923, vol. 43, p. 458) on the laws of heat transmission between walls and fluids as enunciated by Dieterlen (Chaleur et Industrie, June, July, August, September, October, and November 1921). Preussler denies that the heat transmission increases with the speed at which the gases traverse the system. Nusselt, on the other hand, contends that when the rate is increased, both the temperature of the air and the amount of heat transmitted per unit of heating surface increase, notwithstanding that the air remains a shorter time in the apparatus.

Equations are given establishing the paradoxical result that when the diameter of the channels is reduced, that is to say when the heating surface is less, the heat transmitted becomes (in cases where the volume of the air remains a constant) greater and the air is heated more quickly. This important result is due solely to the beneficial influence of the rate of speed upon the coefficient of heat transmission itself. Further work by Nusselt, in conjunction with Jürges, has since become available and confirms these results (Gesundheits-Ingenieur, 1922, p. 641).

M. Laffargue, *Calculation of Continuous Thermal Exchanges* (Chaleur et Industrie, March 1924, vol. 5, pp. 133–137).

R. Calvert and L. Caldwell, *Loss of Heat from Furnace Walls* (Industrial and Engineering Chemistry, May 1924, vol. 16, pp. 483–490). The paper is one of a group of papers forming a symposium on the subject of heat transfer and transmission of heat through metals and insulating materials. The construction and method of working of a thermal conductivity cell for the measurement of the thermal conductivity of different materials is illustrated and described. Tests on furnaces with uninsulated walls and walls insulated with different grades of silocel show that the insulated wall loses 40 per cent. less heat than the uninsulated wall at temperatures of  $980^{\circ}$  to  $1000^{\circ}$  C. A layer of silocel of 1.5 inch thick has an insulating value equivalent approximately to 9 inches of firebrick or silica brick. The surface emissivity of a wall as affected by its colour, texture, or composition is only a small factor in heat losses from high temperature furnaces, and it is the temperature gradient between the inside and outside faces of the furnace wall that determines the heat loss. The higher the temperature of the furnace, the more effective is a layer of insulation in preventing loss heat.



## FUEL.

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## I.—CALORIFIC VALUE.

**Calorimetry.**—C. de la Condamine, *Direct Determination of Calorific Values of Solid and Liquid Fuels* (Chaleur et Industrie, February 1924, vol. 5, pp. 85–91). A description of the principles and apparatus employed in calorimetric determinations by the Mahler bomb method. The details of a number of determinations by this method are given, and the formulæ involved are explained and illustrated by means of practical examples.

C. Berthelot, *Standardisation of the Methods of Testing Coal, Metallurgical Coke, and Briquettes* (Chimie et Industrie, May 1924 (Special Number), pp. 167–207).

**Fuel Economy.**—Sir Robert Hadfield, *Fuel Economy and the Measurement of High Temperatures* (Paper read before the World Power Conference: Iron and Coal Trades Review, August 15, 1924, vol. 119, pp. 273–274). The first section of this paper forms an introduction recalling the importance of fuel economy during the late war and the post-war period. The second section is devoted to a survey of the fields where pyrometry has enabled accurate heat balances to be obtained for steam boilers, forge furnaces, furnaces for the heat treatment of steel, and steel melting furnaces. The remainder of the paper deals with temperature colours.

*Exhibition of Industrial Heating* (Chaleur et Industrie, April 1924, Supplement). A full account of the organisation, proceedings, and exhibits at this exhibition, held in Paris at the Conservatoire National des Arts et Métiers, from June 1 to 17, 1924.

A. Cornu-Thenard, *Tenth Report of the Committee for the Utilisation of Fuel* (Bulletin de la Société d'Encouragement, October 1923, vol. 135, pp. 1029–1052). A summary of the coal consumption in the heavy industries, and more especially in the iron and steel trades in France. Details are given of the amount of fuel used in various stages of the

manufacture of iron and steel, and heat balances are given showing the proportion used in practice, and the theoretical requirements at coke-ovens, in blast-furnaces and Cowper stoves, in open-hearth furnaces and in gas-producers, and finally in the subsidiary operations of rolling, and in the mill reheating and finishing furnaces.

W. S. Coates, *Utilisation of Low-Grade and Waste Coals in Power Production* (Journal of Society of Chemical Industry, May 23, 1924, vol. 43, pp. 157-163T). The author defines the coals classed as low-grade and waste and describes the mechanical stokers of the Babcock and Wilcox and of the Underfeed Stoker Company's types which have been designed for firing with these coals. Means are suggested for maintaining a high efficiency in boiler plants and a brief account is given of the central and unit systems of pulverised coal firing under boilers.

**Combustion of Fuel.**—G. E. Scholes, *The Combustion of Fuel* (Transactions of the Liverpool Engineering Society, 1923, vol. 44, pp. 322-364). The author deals with the principal methods and apparatus used for determining the percentage of carbon dioxide in the products of combustion of various kinds of fuel. A brief résumé of the chemical reactions involved in the combustion of fuels is appended.

A. Linguet, *Considerations relative to Heat Balances* (Chimie et Industrie, November 1923, vol. 10, pp. 829-835). The drawing up of heat balances enjoys a certain vogue, and by its mathematical character appears to afford a valuable means of ascertaining how economies can be effected in industry. It is doubtful whether, however, in view of the diversity of the factors and their complex nature, the reliance placed on heat balances, as commonly drawn up, is justified. The main factors of the problem are stated and the chemical reactions involved in combustion discussed. Examples are given of the paradoxical results which may be derived from the classical treatment of the subject. The estimation of carbon dioxide, oxygen, and carbon monoxide alone may lead to the most misleading results. Instances are given of how certain data are to be interpreted if the results are to be really trustworthy, and directions are given for methods of gas analysis which may serve to eliminate some of the errors commonly introduced in such processes. The constitution of the gases during any given period of burning coal fails to give a true indication of what is happening, as it is affected by the conditions prevailing previous to the actual sampling. The burning of the fixed carbon yields gaseous products which mask the true nature of the gaseous products due to the combustion and distillation products of the volatile matters, and this consideration suffices to vitiate many of the conclusions which are often drawn from considering the bulk gases as representative of heat and chemical reactions actually occurring.

G. T. Southgate, *Boosting Flame Temperatures with the Electric Arc* (Chemical and Metallurgical Engineering, July 7, 1924, vol. 31,

pp. 16-19). An account of a newly developed method of increasing the heat available from fuel combustion by the application of electricity. The pyroelectric process has been applied in typical operations of melting and smelting. A description of the furnace employed and applications of the process are described.

**Pulverised Coal.**—E. Audibert, *Experimental Investigations on the Combustion of Pulverised Coal* (Revue de l'Industrie Minérale, Mémoires, January 1, 1924, pp. 1-32). Early attempts to use pulverised coal directly in the combustion chamber or hearth led to the formation of black smoke, which showed that much of the fuel was not consumed. Experiments were carried out on the injection, from suitable injectors, of the dust into brick chambers which had previously been heated to a high temperature. In such chambers the proper reactions can take place with ease, and useful conclusions as to the best means of employing powdered fuel, and an insight into the laws governing its combustion, are drawn from the experimental results obtained.

J. A. de Grey, *Experiments on Powdered Fuel and the Combustion of Pulverised Coal* (Chaleur et Industrie, January 1924, vol. 5, pp. 23-26). An account, with details and formulæ, of experiments carried out at the testing station at Liévin before the war, and subsequent investigations at Montluçon. The principles governing the design of burners, the speed of the pulverised coal through the burners and on emerging therefrom, the most efficient grouping of the burners themselves and the shape and size of the combustion chambers are first described, after which formulæ are given for ascertaining, in given mixtures of pulverised fuels ranging from low grade to all-coal mixtures, the inflammability, and therefore the limit of safety, and the conditions in which such mixtures can be used. Mixtures of pulverised coal and low-grade gases are also discussed.

C. Roszak, *Physical Properties of Powdered Coal of Varying Degrees of Fineness and the Distribution of Ash and Volatile Matter among the Fractions of Different Size* (Fuel, 1924, vol. 3, pp. 161-165). When coal is crushed to varying degrees of fineness, the finer particles contain more and the coarser particles less ash than the average sample. The increase in ash content with increasing fineness is also apparent in the colour of the fractions. The content of volatile matter usually decreases with increasing fineness, but this diminution does not always correspond with the increase in ash.

K. Kreisinger, J. Blizard, C. E. Augustin, and B. J. Cross, *Investigation of Powdered Coal as Fuel for Power Plant Boilers* (U.S. Bureau of Mines, 1923, Bulletin 223, 92 pp.). The report gives the results of an extensive series of tests made on a 468-horse-power Edge Moor boiler fired with pulverised Illinois coal.

D. Brownlie, *Pulverised Fuel and Efficient Steam Generation* (Journal of the Institution of Electrical Engineers, 1924, vol. 62, pp. 385-418). The author gives a detailed description of the latest developments in

the use of pulverised coal for steam generation. He describes the installation at Lakeside Station, Milwaukee, giving working costs and also the River Rouge plant of the Ford Motor Company at Detroit.

C. H. S. Topholme, *The Use of Pulverised Fuel in Malleable Foundries* (Foundry Trade Journal, September 11, 1924, vol. 30, pp. 214-215). The factors involved in the application of pulverised fuel firing to malleable iron furnaces are discussed.

*Pulverised Coal for Malleable Furnaces* (Iron Age, June 5, 1924, vol. 113, pp. 1633-1635). An illustrated account describing the application of pulverised fuel to malleable furnaces at an American foundry.

**Fusibility of Coal Ash.**—F. S. Sinnatt and N. Simpkin, *Melting Point of Coal Ash* (Lancashire and Cheshire Coal Research Association, 1924, Bulletin No. 15). The authors have devised a method for the determination of the melting point of coal ash, so that it may be carried out on as little as 0.2 gramme of the ash. The melting point of the ash from the separated four constituents of coal—vitrain, clarain, fusain, and durain—differs in different seams and in different horizons in the same seam within wide limits, and bears no apparent relation to its chemical composition.

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## II.—COAL.

**Africa.**—M. D'Oulhaye, *Coal in the Congo* (Revue Universelle des Mines, December 1923, vol. 19, pp. 141-142). A note on the Katanga deposits, one of which occurs in the Tanganyika district, and the other near Bukama, on the Luena. The Tanganyika deposits consist of five seams and aggregate a thickness of over 16 feet. The coal-field has a considerable area, and the amount available is estimated at over 1,000,000,000 tons. With the development of the region, which is healthy, populous, and fertile, an output of 100,000 tons per annum is probable. Much of the coal can be got through adits and opencast workings. The calorific value is 5500 to 6000 calories; the fixed carbon 42 to 45 per cent.; the volatile matter 34 to 40 per cent., while the ash varies from 12 to 20 per cent. In mixtures with Luena and Rhodesian coal it cokes readily.

A. D. N. Bain, *Udi-Okwoga Coalfield* (Geological Survey of Nigeria, 1924, Bulletin No. 6). The author describes the Emugu area of the Udi-Okwoga coalfield, which was discovered in 1909. The coal is made up of alternate dull and bright layers; it has a well-developed cleat and is non-caking. There are five persistent coal-seams, the thickness of which varies from 4 to 64 inches. Recent experiments carried out in England indicate that it is not impossible to make a coke of metallurgical value from Nigerian coal.

H. B. Maufe, *Coal Resources of Southern Rhodesia* (Paper read



before the World Power Congress, London, July 1924). The coal resources of Southern Rhodesia are estimated at 6814 million tons, of which 98 per cent. is suitable for steam-raising. The characteristics of the coal at the Wankie Colliery, which is the only producing coal-mine, may be gathered from the following analysis of eighty-eight samples: Moisture, 0.76; volatile and organic matter, 23.77; fixed carbon, 65.70; ash, 9.77 per cent. The Wankie coal produces a satisfactory metallurgical coke. The plant of the Wankie Colliery Company consists of 140 Coppee retort ovens and 26 beehive ovens. An analysis of the coke is as follows: Moisture, 1.12; volatile and organic matter, 2.05; fixed carbon, 83.63; ash, 13.20; sulphur, 1.15 per cent.

**Bulgaria.**—D. A. Wray, *Mineral Resources of Bulgaria* (Mining Magazine, 1924, vol. 30, p. 73). Within the last ten years the output of coal in Bulgaria has been more than doubled, and now exceeds a million tons per annum. Anthracitic coal is worked on a small scale to North Western Bulgaria, but the ash content is high. Bituminous coals are also worked on a small scale in the same region, but the chief bituminous area is in the Central Balkan range, north of Kazanlik, and Siliven. The coal is of a friable nature, but it is an excellent coking coal, producing high-grade briquettes. Bulgaria is comparatively rich in lignites of Tertiary Age. The principal mines, those at Pernik and Bobovdol, west of Sofia, are worked by the State.

**Canada.**—B. Rose, *Structure in the Crowsnest Coal Area, Alberta* (Monthly Bulletin of the Canadian Institute of Mining and Metallurgy, October 1924, No. 150, pp. 609–619). The author outlines the geology of the Crowsnest coal area, and briefly discusses some of the structural problems which are encountered in locating and mining the coal-seams.

R. J. Lee, *The Lignites of Saskatchewan* (Transactions of the Canadian Institute of Mining and Metallurgy, 1923, vol. 26, pp. 192–205). The only part of Saskatchewan that has been systematically examined for lignite is that portion known as the Souris Valley, and its surrounding districts. In this district there are four seams being worked, which vary in thickness from  $3\frac{1}{2}$  to 15 feet, with an average thickness of 8 feet. There are, however, three other coal areas which are probably as extensive as that of the Souris Valley. The most promising method for increasing the value of the coal consists in a low temperature carbonisation followed by a briquetting of the residue. An investigation of this method has been carried out in the laboratory and on a semi-commercial scale.

**China.**—C. C. Wang, *The Coal-Field of Tatung, Shansi* (Bulletin of the Geological Survey of China, October 1921, No. 3, pp. 71–74). The stratigraphy, structural geology, and coal resources of this field are briefly described.



L. F. Yih, *The Geology of Hsi-Shan or the Western Hills of Peking* (Memoirs of the Geological Survey of China, Series A, No. 1, February 1920). A detailed account is given of the coal-fields of this region, together with a summary of the occurrences of iron ore and other minerals.

T. O. Chu, *Geology of the Lei-Yang Coal-Field, Hunan* (Bulletin of the Geological Survey of China, October 1921, No. 3, pp. 75-77).

H. C. T'an, *Geology of the Tzu-Ch'lan Po-Shan Coal-Field, Shantung* (Bulletin of the Geological Survey of China, October 1922, No. 4, pp. 81-90).

**France.**—H. Pagezy, *Note on the Lignite Resources of Herault and of Aude* (Annales des Mines, 1923, vol. 4, pp. 341-366). Numerous deposits of lignite occur in both these Departments, and their occurrence has been known for many years. During the war the scarcity of fuel led to their further exploitation. The geology of the deposits is briefly described. The largest occurs at Montoulieu, and lignite also occurs not far from Montpellier. The lignite from the former beds contains 17.8 per cent. of ash, and is estimated at a million tons, with probable reserves varying from four to eight million tons. The Montpellier deposits are very high in ash, some of them reaching as much as 40 per cent. Probably the most important deposits are those which occur in a third region, not far from Carcassonne. The volatile matter in these lignites is 46.2 per cent., with 35.8 per cent. of fixed carbon, and 14.6 per cent. of ash. The sulphur is high, being returned as 9.7 per cent.

**Germany.**—Frezouls, *The Rhenish Lignite Industry* (Revue de l'Industrie Minérale, Mémoires, November 15, 1923, pp. 627-666; December 1, pp. 675-700; December 15, pp. 709-730; January 15, 1924, pp. 34-53). An exceedingly detailed account of the lignite or brown-coal industry of the Rhine. Part I. deals with the classification, composition, and properties of lignite; its geological formation and a description of the Cologne field. Part II. deals with the method of mining, both by open cast and underground workings. Part III. describes the washing, drying, grading, and briquetting of the coal; while Part IV. is devoted to a consideration of working costs, outputs, and selling prices. While chiefly the brown-coal deposits are dealt with, the term lignite is applied to all the tertiary deposits found in the Rhine province. The brown-coal is characterised by high moisture contents (50 to 60 per cent.), low calorific power (1800 to 2000 calories), and the property of caking without the addition of tar or other agglomerant. The chief combustible minerals of the tertiary age comprise sapropelite, the product of vegetable decay out of contact with air; humus rock, which constitutes the greater part of lignite, properly so-called, and liptobiolith, which comprises waxes and fossil resins. The varieties of sapropelite recognised are *Blätterkohle* (foliated

lignite), which falls into flakes on drying; *Kieselkohle*, an impregnated sandstone; *Oelschiefer*, or bituminous schist; *Schieferkohle*, or schistic lignite; *Stinkkohle*, a badly smelling lignite; and *Alaunkohle* and *Alaunton*, which are respectively lignites and clays rich in alum and worked for their yield in that salt. The ultimate structure, micro-constituents, and chemical composition of various lignites are described, their chemistry being minutely detailed. The geological and geographical distribution of the chief lignite or brown-coal deposits of Central Europe are also described, and illustrated with maps and diagrams, and the thickness and depth of the chief seams in the Cologne bed are likewise tabulated, the nature of the roof and floor being given, together with an account of the fossils encountered. The section devoted to methods of mining and that dealing with the processes of preparing the coal for market, briquetting, &c., are likewise minutely detailed, the descriptions being accompanied by copious illustrations of the plant and appliances employed.

**Great Britain.**—C. H. Lander, *Physical and Chemical Survey of the National Coal Resources of Great Britain* (Paper read before the World Power Conference, London, July 1924; *Iron and Coal Trades Review*, July 4, 1924, vol. 109, pp. 7–8).

M. MacGregor and E. M. Anderson, *The Economic Geology of the Central Coal-Field of Scotland, Area VI.* (Memoirs of the Geological Survey of Scotland, Edinburgh, 1923). This Memoir deals with the sixth and largest of the nine areas into which the Central Coal-Field of Scotland has been divided for the purpose of detailed geological description. Area VI. comprises the eastern and south-eastern margins of the Lanarkshire Basin, and includes such important coal-mining districts as Bathgate, Wilsontown, Fauldhouse, Shotts, Harthill, Armadale, and Westeraigs.

**Ireland.**—*Exploitation of an Ulster Coal-Field* (Engineering, August 1, 1924, vol. 118, p. 175). A coal area of considerable promise has lately been developed in the district known as Coal Island, near Lough Neagh, 50 miles by rail or canal from Belfast. Boring operations revealed the existence of a good bituminous coal-seam at a depth of 433 feet, and two shafts have now been sunk to a depth of 1070 feet. Within the depth of the shafts there are no fewer than twelve coal-seams, the thickest of which, at a depth of 542 feet, measures 9 feet 6 inches in thickness. A yield of 100,000 tons of coal per annum for a period of four years is anticipated, but there is much coal in the surrounding basin which has not yet been fully surveyed.

**Jugo-Slavia.**—M. Dolch, *A Study of the Coals of Jugo-Slavia* (Montanistische Rundschau, June 1, 1924, vol. 16, pp. 261–265). The occurrences of coal in Jugo-Slavia are noted, and analyses of the coals being worked in various mines are given.

**United States.**—W. T. Lee, *Coal Resources of the Raton Coal-Field, Colfax County, New Mexico* (United States Geological Survey, 1924, Bulletin 752). An account is given of the general geological features and the coal resources of the developed part of this coal-field.

**Coal Resources of the World.**—Sir Richard Redmayne, *Coal Resources of the World* (Paper read before the World Power Conference, London, July 1924; Iron and Coal Trades Review, July 4, 1924, vol. 109, p. 7). The author points out that coals of the highest quality exist in America and Europe, and that America has coal resources far exceeding those of the whole of the rest of the world. In respect of the duration of supplies on the present basis of production, the North American resources, and more especially those of the United States, will outlast all other countries, for her supplies will probably suffice for 2000 years. Of the other great producing countries Great Britain does not stand anything like so well in point of the duration of her supplies, for at the present rate of production Great Britain's coal life will not exceed at most 600 years, and if only the coal existing to a depth of 4000 feet is taken into consideration, it is doubtful whether the supply will suffice for much more than 450 years. Particulars are included showing the world's resources of the different classes of coal.

**Constitution and Chemistry of Coal.**—J. Roberts, *Origin of Anthracite* (Proceedings of the South Wales Institute of Engineers, 1924, vol. 40, pp. 97–138). According to the author, anthracite is a natural product of low temperature carbonisation, the original substance having consisted of bright coal of low ash content, which subsequently attained a temperature of 500–550° C. in the earth's crust. The close similarity between semi-coke produced at 500° and anthracite, both in regard to properties and behaviour under thermal and chemical treatment, support this view.

E. Audibert and A. Raineau, *Modern Theories on the Chemical Constitution of Solid Fuels* (Revue de l'Industrie Minérale, Mémoires, March 15, 1924, pp. 127–172; Chimie et Industrie, February 1924, vol. 11, pp. 229–247). Ignorance of the nature and chemical constitution of solid fuels has in the past led to most of the methods of combustion being purely empirical, the true nature of the reactions involved being imperfectly understood. Instead of attempting to determine, from the fuel as it actually exists, which is an end product of innumerable synthetic reactions, the nature of these constituents, the author employs an inverse process of reasoning, and seeks to ascertain the method by which they have been built up from their component elements. Coal, for example, is of vegetable origin, and the vegetable material from which it has been evolved is of essentially the same chemical description as the vegetation of the present day. The reactions and processes of the present will therefore resemble those of the past, and their investigation will throw a light on the complex constitution of

existing fuels. Peat and lignite represent intermediate stages in the evolution of coal, and must be studied accordingly. Broadly speaking, the original substances from which coal has been derived consist, as to roughly 5 per cent., of waxes and resins. 60 to 75 per cent. consists of carbon hydrates, and 25 to 30 per cent. is lignose. These figures refer to the solid constituents of vegetal matter, and do not include water. An attempt is made to trace, through a study of their decomposition products and reactions, the chemical constitution of the resulting coal. Numerous constitutional formulæ and molecular diagrams accompany the text, the main headings of which are: the carbon hydrates; the lignoses; the humic acids; the transition of vegetable matter to humic bodies, and of humic acids to humates; and, finally, the part played by the associated waxes and resins in the sequences of reactions which have determined the ultimate result.

Connerade, *A Scientific Study of Coal* (Revue de l'Industrie Minérale, Comptes Rendus, March 15, 1921, pp. 51-56) deals with the same subject from a somewhat different angle, his object being more to ascertain the value the constituents may possess as raw materials in technical industries.

C. N. Kemp, *The X-Ray Analysis of Coal and a New X-Ray Examining Unit* (Journal of Society of Chemical Industry, July 18, 1924, vol. 43, pp. 234-235T). The methods of research applicable to the investigation of coal by X-rays resolve themselves into three main groups: (1) Bombardment of the material by rays of known penetrating power and intensity, and observation of the possible modifications effected. (2) Examination by radiosopic and radiographic methods of the general nature and distribution of the extraneous matter in coal. (3) Examination of the elementary crystalline constituents of the coal substance, and of its fixed or free mineral content, by X-ray diffraction. An outstanding feature of X-ray technique as applied to coal is that it provides a means whereby immediate and definite information regarding a specimen may be obtained without altering it in any way. Most striking is the effect obtained by stereoscopy, whereby the inner structure of a totally opaque lump of coal or coke is laid bare for detailed examination, all the mineral impurities being seen in natural perspective. An examining unit of novel design consists of a steel tank, provided with a lid of insulating material, and containing a high tension transformer with a coolidge tube of the radiator type clamped above it, so that the cone of rays from the target of the tube is projected vertically upwards through a suitable glass or aluminium window situated about the centre of the lid.

H. F. Yancey and S. W. Parr, *Sulphur Forms in Coal; Distribution and Control* (Industrial and Engineering Chemistry, May 1924, vol. 16, pp. 501-508). Whereas organic sulphur is uniformly distributed in coal from a given level in a mine, pyritic sulphur is very irregularly distributed, and to this fact is largely due the variation in the total sulphur. The pyritic sulphur only can be removed by mechanical



cleaning processes. Various types of Pennsylvania coal have been classified on a basis of sulphur occurrence and sulphur removal.

J. I. Graham, *Pyrites as a Cause of Spontaneous Combustion in Coal Mines* (Transactions of the Institution of Mining Engineers, 1924, vol. 67, pp. 100–113). A comparison of the amount of oxidation in coal due to pyrites and due to carbonaceous matter, made by tests on a complete section of a South Wales coal-seam, shows that the main source of spontaneous heating is pyritic material, and that the lower portions of the seam will be more troublesome. The presence of moisture is essential to the production of heat consequent upon the absorption of oxygen from the air.

T. J. Drakely and J. R. I. Hepburn, *The Specific Gravity and Ash Content of Coal* (Journal of the Society of Chemical Industry, August 22, 1924, vol. 43, pp. 277–278T). There is no relation between the true and apparent specific gravities and ash contents of clean coal samples from the same seam. For average coal samples, however, a definite relation exists which admits of mathematical expression, but the equation fails when the coal samples contain varying proportions of iron pyrites.

G. Charpy and G. Decorps, *Determination of the Oxidisability of Coal* (Comptes Rendus, May 12, 1924). Nitric acid with a specific gravity of 1.30 is used as the agent for oxidising coal at a temperature of 20° C. The results of the observation are said to be of value in judging the coking properties of coal.

**Occurrence and Preparation of Peat.**—B. F. Haanel, *Peat Resources of the Central Provinces and their Utilisation for Fuel Purposes* (Transactions of the Canadian Institute of Mining and Metallurgy, 1923, vol. 26, pp. 206–241). The properties of Canadian peat are outlined, and the methods of utilising peat as fuel are described.

R. Klasson, *Hydro-Peat* (Zeitschrift des Vereines Deutscher Ingenieure, June 7, 1924, vol. 68, pp. 601–605). A description is given of a method and machinery developed in Russia for winning peat by the use of high pressure water jets which loosen the peat beds, and the peat sludge formed is then lifted by pumps and discharged on to drying beds, where it is chemically treated, dried, and cut into blocks.

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### III.—COKE.

**Coke-Oven Plant.**—*New Wilputte Coking Plant at the Fell Coke Works of the Consett Iron Co., Ltd.* (Iron and Coal Trades Review, May 30, 1924, vol. 108, pp. 909–910). This plant comprises 60 ovens in one battery. The coking chambers and upper parts of the regenerators are constructed of silica brick. The battery has a throughput of



over 6000 tons of dry coal per week. The equipment of the ovens and by-product plant is described and illustrated.

*The Becker By-Product Coke-Oven* (Iron and Coal Trades Review, August 8, 1924, vol. 109, pp. 233-234). An illustrated description is given of the design of this coke-oven, the chief feature of which is the employment of cross-over flues, each of such flues dealing with the gas from only a few vertical flues. An horizontal flue of small area conveys the gas from the vertical flues to the nearest cross-over flue. The small horizontal flues are arranged so as not to interfere with the temperature at the top of the charge, which allows this portion to be coked at practically the same temperature as the bottom of the charge. Another feature of this oven is the adjustable air port which controls the movement and the direction of the air coming from the regenerators into the oven flues. By altering these ports the air can be projected at a flatter or a sharper angle into the heating flue, so that they can be set for the ignition of the gas to take place at the most suitable elevation, thus producing a shorter or longer flame, and any whirl of the air entering the flue is eliminated.

A. Grebel, *The Coke-Ovens and Recovery Plant of the Société Normande de Métallurgie* (Génie Civil, June 21, 1924, vol. 84, pp. 585-593). A fully illustrated description of these new works is given, with an account of the operations of coking and by-product recovery.

**Preparation of Coal for Coking.**—H. M. Chance, *Production of High Grade Blast-Furnace Coke* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1924). The author discusses the possibilities of securing better coking coal, and the utilisation of coal heretofore considered unsuitable for coking. Coals in which the inherent ash is high, say 10 per cent., may often consist of an admixture of coal ranging from 2 to 20 per cent. ash, and to produce from such a coal a low ash product it is therefore only necessary to separate the low ash coal from that of higher ash content. The results obtained by differential separation are outlined. Differential separations can be made by the use of any liquid having a specific gravity greater than that of the coal which is to be floated and less than that of the coal that is to be separated by sinking in the liquid. No liquids or solutions suitable for making such separations on a commercial scale have as yet been discovered or artificially produced. The nearest approach to such liquid is a mechanical mixture of sand and water, in which the sand is kept suspended by agitation. This method of coal separation is known as the sand flotation process.

T. M. Chance, *Application of Sand Flotation Process to the Preparation of Bituminous Coal* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1924). The apparatus used in the washing of coal by this process is described. The general arrangement of a typical plant, operating results, maintenance costs, and estimates for the construction, operation, and capital costs, for a bituminous washery are given.

**Manufacture and Properties of Coke.**—C. Berthelot, *Modern Methods of Working Coke-Ovens* (Société des Ingenieurs Civils; Génie Civil, April 12, 1924, vol. 84, p. 363). The author discusses the design of coke-ovens and coke-oven practice. Silica bricks have lately been introduced for coke-oven construction in Holland and other countries, and have given good results, notably in enabling the coking time to be reduced.

H. H. Berger, *Influence of Temperature of Coking on the Properties of Blast-Furnace Coke* (Gas- und Wasserfach, 1924, vol. 67, pp. 424–425). Specimens of coke were prepared on a laboratory scale, using 700 grammes of coal in a coking apparatus to produce each specimen. Six samples of coal were coked at 500°, 600°, 700°, 800°, 900°, and 1000° C. respectively. Determinations showed that the temperature of ignition and crushing strength increased with the coking temperature, the ignition point being dependent on the volatile matter in the coke. The porosity bore no relation to the temperature, but determined the rate of combustion of the coke. The carbon of all the cokes began to reduce iron oxide at 850°, the reaction attaining a maximum between 925° and 950°, but reduction of the iron oxide by the volatile constituents of the coke took place between 600° and 700°.

W. Mathesius, *Uniform Coking Coal as a Factor in Blast-Furnace Economy* (Paper read before the American Iron and Steel Institute, May 1924). A wide range of irregularity is the outstanding feature of the blast-furnace fuel supply at a majority of plants. Variations in coking ash cause a disturbance of the hearth equilibria, and accordingly affect the blast-furnace process. In the blast-furnace burden the coke is the principal source of sulphur, the satisfactory elimination of which, in the furnace hearth, requires a definite combination of temperature, slag composition, and slag volume. Every variation of the ash content in the coke is necessarily accompanied by a corresponding change of its carbon percentage and fuel value. Irregular ash content of furnace coke denotes variation in the composition of the coal from which the coke is produced. Charging irregular coal in the ovens always varies the heat requirements of the coking process, and therefore disturbs its thermal balance, the accurate maintenance of which is a most important pre-requisite to the making of physically uniform coke. In spite of regular heat input and otherwise best practice, the production of coke with variable physical characteristics becomes unavoidable. This physical irregularity has a serious effect on blast-furnace economics, because its influence is not confined to a disturbance of the equilibria in the furnace hearth, but extends directly throughout the entire furnace process. There is only one possible remedy, and that is the regulation of the blast-furnace fuel supply, in accordance with the principles of the iron ore trade.

J. D. Davies and P. B. Place, *Thermal Reactions of Coal during Carbonisation* (Industrial and Engineering Chemistry, June 1924, vol. 16, pp. 589–592). Samples of different kinds of American coal were investigated during carbonisation, with a view to studying their

thermal behaviour. The method used was that of Hollings and Cobb, in which the rate of heating of the coal sample in a resistance furnace is compared with that of a sample of coke under similar conditions. The direction of the temperature time graph, with the coke curve as base line, indicates whether the reaction is exothermic or endothermic at any temperature.

G. E. Foxwell, *Plastic State of Coal* (Fuel, April, May, July, August 1924, vol. 3, pp. 122-128, 174-179, 227-235, 276-283). The plastic curve of coal is obtained by determining the pressure in millimetres of water required to force a given quantity of gas through a plug of coal of given size, packed in a tube of known cross-section, and heated to definite temperatures in a specially designed apparatus. For rates of increase in temperature of  $1^{\circ}$  to  $4^{\circ}$  per minute the general shape of the curve remains the same for any one coal, but if the rate of heating is altered the curve for the coal becomes distinctive. The faster the rate the greater the resistance to the passage of the gas and the higher the temperature at which the resistance becomes very low owing to the coal ceasing to be plastic and forming coke. The results are applied to the investigation of the path of travel of the gases in the coke-oven and of the temperature of formation and path of travel of the principal by-products. The general physical phenomena associated with the plastic state of non-coking and coking coals are discussed.

D. J. W. Kreulen, *Influence of Particle Size of Coal Samples on the Yield and Character of Coke and on the Ash Content* (Brennstoff-Chemie, 1924, vol. 5, p. 233).

H. W. Anderson, *What Constitutes Good Foundry Coke* (Foundry, September 15, 1924, vol. 52, p. 717). A short discussion on the characteristics of good foundry coke. Comparative analyses of different cokes and the loss sustained by excessive moisture are tabulated.

A. R. Powell and J. H. Thompson, *A Study of the Desulphurisation of Coke by Steam* (Carnegie Institute of Technology, Bulletin No. 7; Colliery Guardian, August 22, 29, 1924, vol. 128, pp. 484-485, 545-546). The results are given of an investigation of the steaming of coke. It was found that 10 and 15 per cent. of the total sulphur in the coke is removed by simple steaming at  $750^{\circ}\text{C}$ . With alternate vacuum and pressure treatment the desulphurisation is increased to 20 or 25 per cent. However, it is possible that the steaming is much more beneficial than the actual sulphur reduction indicates, since the sulphur removed is almost entirely taken from the surface of the coke, and this surface sulphur may be the part that is easily absorbed by the iron in the blast-furnace. The probable behaviour of coke sulphur in the blast-furnace is discussed.

K. Bunte and W. Fitz, *Causes of Varying Reactivity of Coke* (Gas- und Wasserfach, 1924, vol. 67, pp. 241-243). The ignition temperature of semi-coke produced at  $600^{\circ}\text{C}$ . is raised by heating subsequently to  $1000^{\circ}$ . The volatile matter in the coke is thus reduced, but this is not the cause of the diminished reactivity. The reason is that the

essential structure of the coke is formed below  $600^{\circ}$ , while still in the stage of semi-coke, and the subsequent heating serves mainly to render the coke more dense and to reduce its relative porosity, on which the reactivity largely depends.

*Combustibility of Blast-Furnace Coke* (Revue Universelle des Mines, February 15, 1924, vol. 1, pp. 261-270). The translation into French of the paper on this subject by R. A. Sherman and S. P. Kinney (Iron Age, June 28, 1923, vol. 111, pp. 1839-1844).

F. Heyd, *Structure and Combustibility of Coke* (Brennstoff-Chemie, 1923, vol. 4, pp. 339-340). The author does not agree with Schreiber (Brennstoff-Chemie, vol. 4, pp. 273-275) that low combustibility is due to the formation of graphite through the decomposition of  $\text{CH}_4$ . In the opinion of the author, the ash-forming constituents, which are not combined in the coke in the same manner as in the coke ash, strongly influence combustibility. He assumes the presence in coke of  $\text{Si}_2\text{C}_2\text{O}_2$ , which would account for its hardness and low combustibility as well. On burning the coke,  $\text{Si}_2\text{C}_2\text{O}_2$  would decompose and would not be detected by analysis of the coke ash.

F. Schreiber, *Reply to Criticism of F. Heyd* (Brennstoff-Chemie, 1923, vol. 4, p. 341). The author claims to prove the absence of such compounds as  $\text{Si}_2\text{C}_2\text{O}_2$  in coke. He confirms the  $\text{CH}_4$  graphitisation theory by citing the work of Bone on the decomposition of  $\text{CH}_4$  and other hydrocarbons.

**Low-Temperature Carbonisation.**—C. Berthelot, *Low-Temperature Carbonisation, with Special Reference to Lignites* (Bulletin de la Société d'Encouragement, January 1924, vol. 136, pp. 44-66). Low-temperature carbonisation consists in heating a fuel slowly and uniformly to the temperature at which the maximum yield of tar is obtained, and this temperature is low in proportion to the geological age of the fuel. For ordinary coals it is  $500^{\circ}\text{C}$ ., for lignites it is about  $450^{\circ}\text{C}$ . It is necessary, however, to define precisely what is meant by tar. When a lignite is distilled the following sequence takes place :

Retort Temperatures.	Result.
$110^{\circ}\text{C}$ .	Water distils over.
$155^{\circ}\text{C}$ .	Water ceases to distil.
$190^{\circ}\text{C}$ .	First evolution of (non-inflammable) gases.
$300^{\circ}\text{C}$ .	Oil begins to appear and the gases become inflammable.
$380^{\circ}\text{C}$ .	The flame of the gases become very hot and very illuminating.
$390^{\circ}\text{C}$ .	The heat and luminosity of the flame decreases.
$420^{\circ}\text{C}$ .	The gas flame becomes almost non-luminous.

The temperature  $385^{\circ}$  to  $400^{\circ}$  corresponds with the maximum yield of tars. Above  $500^{\circ}\text{C}$ . little tar oil is obtained. The various products  
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are discussed and tables given of the composition of the oils, the types of retorts used being also briefly described and illustrated. The use of the Fischer rotary oven, which has been successful in Czecho-Slovakia in treating lignites, is recommended on general grounds, and the Salerni low temperature carbonisation process is also advocated. To sum up: low temperature carbonisation proceeds best in continuous ovens with considerable surface heating in narrow spaces, so that the fuel can be in thin layers and not heated beyond  $450^{\circ}$  in the case of lignite, or  $500^{\circ}$  C. in the case of coal. Such processes lead, moreover, to the production of good dense metallurgical coke from flaming coal. The solid residues from low temperature carbonisation of lignite have many valuable fuel applications, such as domestic uses, and for central heating, and the use of pulverised semi-coke from lignite for heating steam turbine and boiler plants will pave the way for highly economical production of electrical energy.

*The Piron Process of Low Temperature Carbonisation of Coal* (Fuel, June 1924, vol. 3, p. 188). The Piron system consists of a double chamber furnace lined with refractory brick, and provided with an endless moving metal conveyor floated on molten lead at a temperature not exceeding  $1300^{\circ}$  F. Powdered bituminous coal is delivered on to the receiving end of the conveyor, and the heat from the lead bath transforms the powdered coal during its ten minutes' passage through the furnace into a non-adherent devolatilised sheet. This drops on reaching the discharge end on to a second conveyor which removes it for storage. Distillation chambers are provided above the conveyor, and the by-products are conducted to a separate plant for further treatment. A plant for treating 400 tons of coal a day has been installed at the works of the Ford Motor Company in Canada, and a larger one is in course of construction at the River Rouge works of the same company.

C. H. Lander, *Low Temperature Carbonisation* (Paper read before the World Power Congress, London, July 1924: Iron and Coal Trades Review, July 4, 1924, vol. 109, pp. 9-10). The developments and future prospects of low temperature carbonisation are discussed.

C. H. S. Tupholme, *Using Internal Heating for Low Temperature Carbonisation* (Chemical and Metallurgical Engineering, June 2, 1924, vol. 30, pp. 861-863). Particulars are given of the following processes of low temperature carbonisation using internal systems of heating: Everard Davies, Illingworth, Koppers, and Plauson.

H. Holzwarth, *A Successful Low Temperature Distillation Process* (Coal Industry, March 1924, vol. 7, p. 112).

C. Berthelot, *Carbonisation at Low Temperatures as a Source of Hydrocarbons and of Electrical Energy* (Revue Universelle des Mines, December 1923, vol. 19, pp. 326-328). Points out the advantages accruing from the richer yields due to low temperature carbonisation, and briefly summarises the results obtained. The following table



shows the difference in the distillation products obtained at 600° and at 900° C. respectively.

	Temperature of Carbonisation.	
	600° C.	900° C.
Spirits and benzols (kgs.) . . .	20	8
Heavy (Diesel) oils " . . .	50	15
Solid hydrocarbons " . . .	2	4
Pitch " . . .	8	20
Gas (cubic metres) . . .	120-150	300-320

C. Berthelot, *Extraction of Primary Tar and Crude Oils from Bituminous Coals and Lignites, by Low Temperature Carbonisation* (Génie Civil, September 6, 13, 26, 1924, vol. 85, pp. 209-213, 230-233, 251-254). Various processes for the extraction of tar and oils are described, and the yield and nature of the products are considered.

G. Paris, *The Low Temperature Manufacture of Tar* (Chaleur et Industrie, March 1924, vol. 5, pp. 127-128). An account of recent practice in Germany, where the loss of the Silesian coalfields has greatly stimulated the most efficient utilisation of the home coal supplies. Low temperature coking and tar distillation has proved highly advantageous, the by-products being richer and relatively more voluminous, while the semi-coke is also of great industrial value. Rotating kilns are employed as they give better results than fixed ovens.

**Coke By-Products.**—F. W. Miller, *By-Product Coking in Alabama* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1924). A brief history is given of by product coke manufacture in Alabama with short general descriptions of plants.

P. Fritzsche, *Coke-Ovens and Liquid Fuels* (Zeitschrift des Vereines Deutscher Ingenieure, June 7, 1924, vol. 68, pp. 593-599). Practice in the recovery of liquid fuels as by-products of the coke industry is described. The products discussed are, first, those obtained in coking at ordinary temperatures; namely, tar, consisting of the whole of the liquid constituents contained in the gases, tar-oil, a product of the distillation of the crude tar, and the light hydrocarbons; secondly, the liquid products of low temperature carbonisation, namely primary tar, primary tar-oils, and primary benzene which correspond with the former, but are quite different chemically; and thirdly, products which have been chemically transformed, such as hydrated solid and liquid hydrocarbons and alcohols from ethylene and allied hydrocarbons obtained from the coke-oven gases.

W. Funcke, *The Recovery of Pitch and Tar-Oils, and Ammonia*

from *Coke-Oven Gases, by the Process of Walther Feld* (Glückauf, September 20, 1924, vol. 60, pp. 835-840).

M. E. Mueller, *Sodium Cyanide as a By-Product of Coke Making* (Chemical and Metallurgical Engineering, June 23, 1924, vol. 30, pp. 978-980). A description is given of a process that permits of the recovery of sodium cyanide or of any other cyanogen compound as a by-product in coking.

#### IV.—LIQUID FUEL.

**Burmah.**—W. J. Wilson, *The Crude Oils of Burmah and Assam* (Journal of Institution of Petroleum Technologists, June 1924, vol. 10, pp. 227-241). The most developed and productive field of Burmah is that of Yenangyoung, followed by Singu and Yenangyat, all in the vicinity of the Irrawaddy river, and 275 to 325 miles from Rangoon. The oils are characterised by their exceptionally high content of solid paraffins, present in such proportions as to cause the oil to set at temperatures below 70° F. The two chief oilfields of Assam are those of Digboi and Badarpur. The Digboi crude oils are similar to those of Burmah, and are singularly free from water, but the Badarpur oils are associated with water. The oil is a natural fuel oil of high specific gravity, and solid paraffins are totally absent.

**France.**—Demay, *The Geology of the Pechelbronn Petroleum* (Revue de l'Industrie Minérale, Mémoires, March 1, 1924, pp. 101-106). A brief account of the geological features of the Pechelbronn deposits designed to facilitate further investigations and borings in the district, and to indicate places when such borings are likely to be attended with commercial success.

*Pechelbronn* (Chaleur et Industrie, April 1924, Supplement, pp. 41-43). An account of the plant, processes and production of the Pechelbronn Mining Company and of the refining of the crude oil. The annual production of the latter is now 100,000 metric tons.

**Germany.**—*The New Petroleum Discovery in Germany* (Petroleum Times, May 10, 1924). Borings have been carried out near Celle in Hanover, and at a depth of 765 metres oil and gas were struck, the production of the well being estimated at 25 to 30 tons a day. This petroleum occurs in salt domes analogous to those of Rumania and Texas. The oil is confined to the Triassic system of beds.

**Mexico.**—C. A. Sansom, *The History and Geology of the Oilfields of Mexico* (Journal of Institution of Petroleum Technologists, June 1924, vol. 10, pp. 306-309). The paper gives a short account of geology of the Mexican oil regions and of the oil industry.

**Morocco.**—R. Abrard, *Petroleum in Morocco* (Bulletin de la Société géologique de France, 1923, Série 4, vol. 22, pp. 145–153).

B. Yovanovitch, *Petroleum in Morocco: The Geology of the Petroleum Deposits in Morocco* (Bulletin de la Société géologique de France, 1923, Série 4, vol. 22, pp. 234–245).

A. Beaugé and L. Joleaud, *Petroleum in Morocco: A Study of the Folding of the Region of Meknès* (Bulletin de la Société géologique de France, 1923, Série 4, vol. 22, pp. 254–284).

The above papers describe the petroleum possibilities of Northern Morocco.

**Persia.**—R. K. Richardson, *The Geology and Oil Measures of South-West Persia* (Journal of Institution of Petroleum Technologists, June 1924, vol. 10, pp. 256–283). The area described comprehends a long belt of petroliferous territory flanking the Persian Gulf on its eastern side, and passing north-westwards towards the boundary of Mesopotamia. The chief oilfield is that of Maidan-i-Naftun, about 140 miles from the port of Abadan, on the Shatt-el-Arab, to which place the oil is transported by pipe line. The production of the field in 1923 was over 788 million gallons, or approximately 3 million tons of oil.

**Poland.**—K. Friedl, *The Oil Production of Poland—Past, Present, and Future* (Petroleum Zeitschrift, April 1, 1924, pp. 377–381). The geological conditions of the Polish oilfields are described, with some account of the industry which in the important fields has long since passed its maximum.

**Roumania.**—B. Yovanovitch, *Petroleum in Roumania* (Bulletin de la Société géologique de France, 1922, Série 4, vol. 22, pp. 11–17).

**Geology of Petroleum.**—C. Finaton, *Petroleum Occurrences* (La Revue Pétrolifère, March 8, April 5, 1924). A summary account of the geological conditions under which petroleum occurs. The Primary rocks are first dealt with, and the second part of the paper discusses the oil occurrences in the Secondary and Tertiary series.

C. E. Orstrand, *Apparatus for the Measurement of Temperatures in Deep Wells by Means of Maximum Thermometers* (Economic Geology, 1924, vol. 19, p. 229). The construction and method of using the apparatus are described.

**Oil Shales.**—W. Forbes Leslie, *The Somerset Oil Shale Fields* (Lecture before Junior Institution of Petroleum Technologists: Engineering, May 30, 1924, vol. 117, p. 714). The Somerset shale oils contain 13·9 per cent. petrol, 11·9 per cent. kerosene, 28·2 per cent. gas oils, 27·5 per cent. heavy lubricating oil, and 18·5 per cent. light lubricating oil. The lubricating oils have specially valuable properties. The large beds of shale between Watchet and the Parrett form a most

important source of heat and power, and in addition to the valuable by-products the ash after retorting contains about 20 to 25 per cent. of fixed carbon. The geological conditions and chemical constitution of the shale beds are described.

R. Brunschweig, *Note on the Bituminous Shale Industry in France* (Annales des Mines, 1924, vol. 6, pp. 5-31). Before the war the bituminous shale industry of the Lyons and Allier regions involved the production of some 150,000 tons and 60,000 tons respectively per annum, but this production fell considerably during the war, and the industry has only recently revived. The practice of extracting the oil is modelled on the methods involved in Scotland. At present the yield in oil is 90 litres per ton, 13 kilogrammes of ammonium sulphate being produced at the same time. The cost of production, and the selling price of the products, are such that the gross difference represents some 20 per cent., but this is subject to a number of charges which in effect make it much lower. The paper is followed by a brief account of the Scotch shale oil industry, and the prospects of both countries in regard to shale oil production are compared.

D. Meneghini, *The Bituminous Chalks of the Abruzzo, and their Possible Utilisation by Distillation* (Giornale di Chimica Industriale ed Applicata, November 1923, vol. 5, pp. 545-549). Reference is first made to the investigations carried out by the technical Committee for the Utilisation of National Fuels, instituted by the Italian Ministry of Agriculture, on the asphaltic rocks of Ragusa, in Sicily, and to such particulars as have been published on the bituminous chalks of Abruzzo. Analyses of various samples are given. Low-temperature distillation ( $500^{\circ}$  to  $520^{\circ}$  C.) gives noteworthy yields. The sulphur is high, but the benzol recovery is rich enough to warrant the utilisation of these deposits on an industrial scale. They also make excellent paving material.

G. de P. Cotter, *The Oil Shales of Eastern Amherst, Burmah, with a Sketch of the Geology of the Neighbourhood* (Records of the Geological Survey of India, 1924, vol. 55, pp. 273-313).

**Production of Liquid Fuel from Coal.**—A. W. Nash, *The Berginisation of Coal and Oil* (Journal of Institution of Petroleum Technologists, June 1924, vol. 10, pp. 329-334). The experiments of F. Bergius in the artificial production of coal are described. By heating cellulose in a water-cooled bomb to about  $340^{\circ}$  C. under a pressure of 200 atmospheres for a period of twelve hours he obtained a black amorphous mass composed of 84 per cent. carbon, 5 per cent. hydrogen, and 11 per cent. oxygen, a quantity of  $\text{CO}_2$  being formed at the same time. He then placed the synthetic product in a bomb together with hydrogen and heated to  $400^{\circ}$  C. at a pressure of 100 atmospheres. It was found that 70 per cent. of the new product could be extracted with benzene, the extract being similar in appearance to a normal mineral oil. Using natural coal, it is claimed that about 90 per cent. of the coal calculated



on an ash and water-free basis can be liquefied. The hydrogenation of crude oils which do not pay for refining has now been undertaken on a commercial scale.

F. Fischer, *The Conversion of Coal into Oils* (Paper read before the World Power Conference, London, July 1924). In the destructive method of dry distillation the yields of oil are relatively small, because on the one hand only certain constituents of coal can be converted into oils by destructive distillation, and on the other hand high-temperature coking represents an exceedingly wasteful process of destructive distillation. If it is required to obtain large quantities of oil by destructive distillation, it is necessary to work at as low a temperature as possible. The point of decomposition of the bituminous constituents is at temperatures which, according to the quality of these substances, lie between 300° and 450° C. Any higher temperature is disadvantageous, changing the oils and forming coke and gas. As opposed to destructive distillation, hydrogenation is a method which converts coal into oleaginous substances up to the weight of the coal. A third possibility for conversion of coal into oils is provided by synthesis from gases. By gasifying coal to water gas, the latter may be transformed into synthetic oil by means of a high-pressure contact process. The synthetic oil mixture, synthol, boils below 200°, and, as it proves to be a suitable substitute for gasoline or benzol, may be employed as a motor fuel.

**Apparatus for Burning Petroleum.**—W. Trinks, *Combustion Devices for Liquid Fuel* (Fuels and Furnaces, 1924, vol. 2, pp. 21–24, 135–138, 255–258). The methods of preparing liquid fuels for combustion and the types of burners used are discussed.

**Economics of Petroleum.**—A. Guiselin, *The Petroleum Refining Industry of Belgium* (Revue Universelle des Mines, December 1923, vol. 19, pp. 321–322). An abstract of a lengthy report on the advantages which would accrue from having a large centralised petroleum refining industry in Belgium, which is favourably situated for drawing overseas and transcontinental supplies of crude oil from all over the world.

## V.—ARTIFICIAL GAS.

**Gas-Producers.**—*The Gerard Mechanical Gas-Producer* (Iron and Coal Trades Review, August 22, 1924, vol. 109, p. 314). A description, together with an illustration showing the sectional elevation and plan of the Gerard mechanical gas-producer, is given. The grate, built up of plates, is almost flat, and is protected from the heat of the incandescent materials by a layer of cinders, which are only slowly discharged. The incoming air is well distributed through the joints in the layers of plates. The rotating body which carries the grate



is in the form of a triangular prism with curved faces, each flanked by a semi-circular inclined plane. These planes act as ploughs, continually turning up the mass of cinder and fuel. The mechanical gearing of the producer consists of a water-cooled crossbar which revolves in a horizontal plane at a fixed distance from the grate.

**Gas-Producer Practice.**—A. H. Lymn, *The Gas-Producer as Applied to Large-Scale Power Generation* (Paper read before the World Power Conference: Iron and Coal Trades Review, July 11, 1924, vol. 109, pp. 58-59). The author deals with the application of the gas-producer to the generation of power on a large scale, and discusses this problem in the light of several combinations:

- (1) Low temperature gas-producer plant combined with reciprocating gas-engines.
- (2) Low temperature gas-producer plant combined with steam boilers and steam turbines or reciprocating engines.
- (3) Low temperature gas-producer plant plus internal-combustion turbines, which are only now becoming available as a commercial proposition.

The economics of the different systems are compared, and tabular comparisons of operating costs are included.

R. Maclaurin, *New Methods of Producing Gas for Industrial Operations* (Transactions of the Ceramic Society, 1923-24, vol. 23, pp. 121-141). An illustrated description is given of the Maclaurin carbonising plant designed for the production of smokeless fuel and industrial gas. The producer is in the form of a small blast-furnace about 45 feet high and 8 feet diameter at the widest part of the interior. The coal is fed in through a hopper placed on the top. The capacity of the producer is about 30 tons when full, and the coal is charged at the rate of about 1 ton per hour, the equivalent coke or residue being withdrawn through doors at the bottom. Air blast is supplied through a large number of narrow brick ports about 12 feet above the discharging doors. By controlling the air blast and the gas passing off, the plant can be changed over in a few minutes from working for low temperature coke to working for complete gasification. The chief point of difference between the Maclaurin plant and the ordinary type of producer is that the former produces coke as well as gas. An average sample of the Maclaurin producer-gas contains:

CO <sub>2</sub> .	O <sub>2</sub> .	CO.	CH <sub>4</sub> .	H <sub>2</sub> .	N <sub>2</sub> .
6.2	0.6	16.0	13.0	16.1	48.1

The calorific value of the gas is 247 B.Th.U. gross.

C. H. S. Tupholme, *Power and Process Steam from By-Product Producer-Gas* (Chemical and Metallurgical Engineering, August 25, 1924, vol. 31, pp. 300-303). A description is given of the L.R.P. low

temperature gasification process. The plant consists of three main factors :

(a) Gasification of coal, with the recovery of by-products ; (b) the generation of steam at high pressure ; and (c) production of power by means of extraction or bleeder turbines.

The process is essentially a combination of the low temperature process for the production of tars, oils, ammonia and gas, with the producer-gas process in a producer-retort in one operation. The boilers for utilising the gas generated are of the Spencer Bonecourt Kirke type.

E. Terres and J. Schierenbeck, *Coke Gas-Producers* (Gas- und Wasserfach, 1924, vol. 67, pp. 257-263, 279-282, etc.). The method of working of two types of coke gas-producers is described, and their performance in the production of gas for heating gas retorts is compared.

F. Clements, *British Steelworks Gas-Producer Practice* (Revue de Métallurgie, Mémoires, January 1924, vol. 21, pp. 42-66). A translation of the paper read before the Iron and Steel Institute at the May Meeting, 1923 (Journal of the Iron and Steel Institute, 1923, No. 1, pp. 97-123).

R. T. Haslam, *Producer-Gas* (Industrial and Engineering Chemistry, August 1924, vol. 16, pp. 782-784). The constituents of producer-gas come to an apparent equilibrium value dependent on the thickness of the fuel bed alone and independent of gas velocity, ratio of coal to pounds of steam, or temperature of the exit gases. A hypothesis explaining this phenomenon is given based on the reaction  $\text{H}_2\text{O} + \text{CO} = \text{CO}_2 + \text{H}_2$ , being catalysed by hot surfaces which the gases can reach only by diffusion.

M. Laffargue, *On the Enrichment of Producer-Gas by the Blowing of Vapour-Saturated Air, and other Improvements in the Yield of Gas-Producers* (Société de l'Industrie Minérale, Comptes rendus, October 15, 1923, pp. 215-222). An account of the results of preheating the air, and adding water vapour thereto in gas-producer practice. Such methods show a great increase in the thermal yield, amounting to as much as 20 per cent. They are specially applicable in the case of lean fuels and coke, and can be adapted to low temperature distillation, in the case of semi-coke. The ammonia recovery can be greatly increased, and such methods have the added advantage of making it possible to get good producer-gas from coke, and so economise the use of bituminous coal.

M. Migeon, *Processes for the Treatment of Peat and Lignite* (Chimie et Industrie, February 1924, vol. 11, pp. 248-255). Two forms of apparatus are described—one for the desiccation and subsequent gasification of raw peat, in the Migeon "Gasefactor," and the other, a kind of producer, with by-product recovery for gasifying lignite. The process, as applied to peat, gives a high ammonia and tar recovery, and a useful industrial gas containing up to 33.1 per cent. of carbon monoxide and 37 per cent. of hydrogen, derived from the water

associated with the peat. About 3 tons of peat containing 58 per cent. of moisture can be treated in the gasefactor per hour.

**Gas for Power and Heating.**—J. W. Brearley, *Exclusive Use of Coke-Oven Gas Supply for Town's Use* (Gas World: Iron and Coal Trades Review, June 20, 1924, vol. 108, p. 1057).

Sir Arthur Duckham, *Use of Town Gas in Industry* (Paper read before the World Power Conference, July 1924: Iron and Coal Trades Review, July 11, 1924, vol. 109, p. 64).

C. H. S. Tupholme, *European Gas-Producer Practice* (Blast-Furnace and Steel Plant, September 1924, vol. 12, pp. 401-406). A short illustrated description is given of modern furnaces fired with producer-gas.

**Use of Blast-Furnace Gas.**—K. Rummel, *Blast-Furnace Gas Economy in German Ironworks* (Paper read before the World Power Conference, London, July 1924; Iron and Coal Trades Review, July 25, 1924, vol. 109, pp. 156-157). The author discusses the most economical methods of using blast-furnace gas. In comparing the different methods of utilisation, a quality factor is used, which is based on the value or price of 1000 calories of steam coal delivered free at German works. When multiplied by the heat value of the gas and the price for 1000 calories of steam coal, the quality factors indicate immediately the value of 1 cubic metre of blast-furnace gas.

**Water-Gas.**—W. W. Odell, *Use of Bituminous Coking Coal as Water-Gas Generator Fuel* (U.S. Bureau of Mines, Technologic Paper No. 274, 1923, 39 pp.).

**Gas-Engines.**—*The New Gas-Engine Plant of the Illinois Steel Company* (Power, April 8, 1924, vol. 59, pp. 552-557). The article describes the four blast-furnace gas-engine units of 3300 kilowatts each which have been installed at the South Works of the Illinois Steel Company.

## VI.—NATURAL GAS.

**Occurrence of Natural Gas in Germany.**—C. A. Heiland, *The Natural Gas Occurrence at Neuengamme near Hamburg* (Zeitschrift für praktische Geologie, July 1924, vol. 32, pp. 89-92). In some trial borings at Neuengamme in November 1910 natural gas was struck at a depth of 247 metres. The gas was used to supplement the supply of town gas of Hamburg, and by 1921 some 200 million cubic metres of the natural gas had been consumed. The pressure having now fallen to about one atmosphere the question of making further borings is under consideration. A geological study of the district leads to the belief that further reservoirs of gas exist at no great depth.

## VII.—COAL WASHING AND HANDLING.

**Coal Washing.**—H. S. Geismer, *Coal Washing Practice in Alabama* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1924). For producing coking coal, three-compartment jigs are favoured; mines supplying steam and commercial coal use single-compartment jigs exclusively. Experiments in Alabama indicate that the sludge released by coal-washing plants can be deposited in streams and on agricultural lands without disastrous results.

J. G. Scoular and B. Duglinson, *The Washing of Fine Coal by the Froth-flotation and Concentrating-table Processes at Oughterside Colliery, Cumberland* (Transactions of the Institution of Mining Engineers, July 1924, vol. 67, pp. 374–389).

J. B. C. Kershaw, *The Improvement of Coal by Mechanical or Thermal Methods of Treatment* (Fuel, May, June 1924, vol. 3, pp. 165–170, 189–195). The article describes various modern types of coal washers.

G. A. Vissac, *Dry Cleaning Plant of the Greenhill Mine of the West Canadian Collieries, Ltd., Blairmore, Alberta* (Monthly Bulletin of the Canadian Institute of Mining and Metallurgy, October 1924, No. 150, pp. 643–653). A brief description is given of the dry cleaning plant in operation at the above-mentioned collieries.

**Coal Handling.**—*Coal and Ore Handling Plant at Waalhaven, Rotterdam* (Engineer, June 27, 1924, vol. 137, pp. 722–725). An illustrated description is given of the new coal and ore unloading plant installed at Waalhaven near Rotterdam. Two transporters of different types are used, the total capacity of the two being about 1000 tons per hour.

## PRODUCTION OF IRON.

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### I.—MANUFACTURE OF PIG IRON.

**Blast-Furnace Design and Equipment.**—M. Derclaye, *Relationship between the Lines of a Blast-Furnace and the Method of Blowing it* (Revue Universelle des Mines, February 1, 1924, vol. 1, pp. 146–162). A detailed mathematical investigation of the subject. The furnaces respecting which data were obtained for the factors in the various equations given were those on a basic pig iron burden in which only minette and Swedish ore was used. Ten such furnaces were involved. The furnaces are considered as belonging to one of two distinct types, the low high-diameter type and the tall low-diameter type, or squat- and slender-lined respectively. The tall furnaces possess certain defects not always easily recognised, such as unnecessarily high pressure of blast and an undue sensitiveness to very small temperature changes. They consume, therefore, more coke in proportion to their “useful capacity” than a squat furnace of the same output. If furnaces of these types are mixed together in one plant and served by the same blast mains, trouble will ensue. The two categories should be blown independently. The general conclusions derived from the investigation, which is accompanied by tables and formulæ, are that the squat form furnace working on minette ore and producing basic pig iron is far more economical than the tall form, and that a very important relation exists between a furnace profile and the mode of driving. Emphasis is also laid on the great advantage of breaking the ore to uniform size. For Swedish and for manganese ore it is essential. For furnaces working under the conditions described, low, wide lines and low pressure blast give the best possible results.

M. Derclaye, *The Number, Shape, Diameter and Position of Blast-Furnace Tuyeres and their Influence on the Behaviour of the Furnace* (Revue de Métallurgie, Mémoires, June, July, and August 1924, vol. 21, pp. 315–337, 396–421, 450–461). The following formula gives the relation between the number and diameter of the tuyeres of a blast-



furnace, its daily output and the temperature, on the absolute scale of the blast :

$$w = 0.00018 \frac{P}{nd^2} \times T$$

When  $w$  is the rate of the blast at the tuyere in metre-seconds ;

$P$ , the coke consumption in tons per twenty-four hours ;

$T$ , the absolute temperature of the blast in degrees centigrade ;

$n$ , the number of the tuyeres, and

$d$ , their diameter, in metres.

The actual diameter is given by the equation :

$$d = \sqrt{\frac{0.00018PT}{nw}}$$

A diagram and tables based on these formulæ enable the various factors of the tuyere problem to be solved, and the most favourable conditions for furnace working can thus be ascertained. There is, however, a practical limit to the number of tuyeres that can be used. The water-cooling expense increases greatly, and may correspond to a considerably greater coke consumption per ton of pig iron produced. Moreover, tuyere trouble rises in proportion to the number of tuyeres, and it is a mistake to assume that the larger the number the more effectively can the blast be distributed in the furnace. Instances to the contrary are given. The more tuyeres the more channels that occur, leading eventually to hanging and scaffolding.

The position of the tuyeres in relation to the hearth is very important, and rules are given for its determination as well as for their arrangement and connection with the blast. The general effect of all these considerations is exemplified by the detailed examination of the balance-sheet of blast-furnaces working on a minette burden, and making basic pig with a coke consumption of 966 kilogrammes per ton, and a daily output of 163 tons. For purposes of comparison other heat balances are included. When, broadly speaking, other conditions are more or less identical, the effective yield and the coke consumption of a furnace will depend very largely on the proper selection of the right number of tuyeres. This is a direct practical outcome, but the actual reasons do not emerge from a general consideration of the heat balance. To find the actual cause of, for instance, reduced coke consumption, the separate balance sheets relating to particular zones have to be considered. This is more difficult to do, but formulæ based on the known physico-chemical reactions are forthcoming which can be applied to the purpose. A number of diagrams have been plotted with this end in view. Even then the information may be incomplete and requires to be supplemented by theoretical deductions from the known data. The final section is therefore devoted to the theories elaborated by Mathesius, by the aid of which a general diagram can be drawn up which will be applicable to any kind of furnace, and can be adapted to any normal range of

working conditions, however diverse. This diagram, which will show the maximum possible yield and efficiency, can be used as a standard of comparison, and serve to check the actual results obtained in practice and to indicate how they can be improved upon.

R. Jordan, *Notes on the Progress Effected in the Blast-Furnace* (Revue de Métallurgie, Mémoires, March, April 1924, vol. 21, pp. 127-142, 223-232). A general view of recent progress in blast-furnace practice, including methods of charging, furnace headgear, the design of the furnaces themselves, the effect of modifications in the furnace lines, and increases in the hearth diameters. Some of the newer forms of charging appliance which are described include the Brown and the MacKee hoists, and the new Gogodsky-Secomet hoist. The Meunier charging system is also fully illustrated, both by photographs and diagrams. In regard to furnace design all the latest tendencies are enumerated, and the reasons given for modifications which have been found in practice advantageous, particularly in American and Continental practice.

G. Jantzen, *The Internal Profiles of Modern Blast-Furnaces* (Stahl und Eisen, June 12, 1924, vol. 44, pp. 681-684). Examples of sections of blast-furnaces are shown, in which the lines of modern types are compared with those of older ones. Modifications in design as introduced by Brassert and Koppers are referred to.

J. R. Briggs, *Dismantling Old Stacks by Blasting* (Iron Trade Review, August 21, 1924, vol. 75, pp. 484-486). The use of dynamite for the demolition of blast-furnace stacks is dealt with.

H. Dresler, *Charging Devices for Blast-Furnaces* (Stahl und Eisen, August 14, 1924, vol. 44, pp. 973-976). The uniform distribution of the burden within the blast-furnace is necessary to secure an even flow of the gases through all parts of the shaft, otherwise irregular working and hanging of the charge may result. The records of the old charcoal furnaces in Styria show that this was well understood in the time when furnaces were charged by hand. The author uses pyrometers to measure the temperature of the gas current at the side of the furnace and at the centre, the point at which the records are taken being some 16 feet below the throat of the furnace. His charts show that at the sides a fairly constant temperature of 50° to 100° is maintained, while at the centre it ranges from 200° to 300°, averaging 250° C. The furnace works best when these temperatures are kept as constant as possible, and any sudden change indicates a loosening or jamming up of the charge. If the temperature tends to rise at the centre it can be brought down by charging fines to the centre, or lump ore if it falls; and by carrying out this plan regularly a much larger proportion of fines can be used. A new method of charging with two buckets is shown, with a bell so designed that the charge is distributed to the sides or the centre of the furnace as desired.

**Blast-Furnace Practice.**—A. Korevaar, *The Law of Heat Compression and Fuel Economy in Blast-Furnaces* (Chimie et Industrie, April

1924, vol. 11, pp. 642-650). It has been previously shown that, taking Le Chatelier's definition of the zone of combustion, any air passing through an ideal gas-producer with a constant speed of  $x$  kilogrammes per minute will burn at the surface of the fuel, and to begin with produce  $\text{CO}_2$ , whereas in the upper layers of fuel the  $\text{CO}_2$  is reduced to  $\text{CO}$ . In any horizontal section where the last molecules of  $\text{CO}_2$  are being oxidised, the phenomena of combustion cease, and this defines the zone of combustion, which starts at the bottom of the producer. If in a furnace the factors relating to design and the air remain constant, the volume of the zone of combustion will depend solely on the factors relating to the fuel, such as its porosity, the size of the lumps, and to some extent its ash content. To simplify the view of combustion, the intermediate stage of the formation of the  $\text{CO}_2$  can be ignored and the whole of the air be regarded as being burned to  $\text{CO}$ . Further, the temperature differences of different horizontal layers may theoretically be disregarded and the temperature be regarded as uniform through the entire zone of combustion. Neglecting the intermediate  $\text{CO}_2$  formation, which is accompanied by the evolution of considerable heat, the average temperature of the zone of combustion will be lower than that given by actual measurements. Now, the air introduces a known amount of heat per minute, and the combustion to  $\text{CO}$  likewise develops a known quantity of heat. The amount of fuel being known and the heat of the waste gases, the amount of "available" heat can be easily arrived at, and the problem reduced to its simplest theoretical factors. Starting from these premises, the conditions leading to heat compression are discussed. In general terms the heat may be concentrated in a smaller volume, thus raising the temperature. Alternatively, by reducing the volume of the zone of combustion by influencing the factors relating to the fuel, but with the same amount of blast per minute, a higher temperature can be obtained with the same fuel consumption. This, considered from a different standpoint, implies that the same temperature could be maintained with a smaller fuel combustion. These three views are developed in detail, and the influence of variables, such as the composition and inflammability of the coke, the preheating of the blast, &c., is then brought to bear upon the elucidation of the laws of heat concentration and distribution and their effect on fuel economy. The mathematics of the subject are introduced in simplified form and without undue complication. Broadly speaking, the lower the blast-temperature the higher the fuel consumption.

P. H. Royster, T. L. Joseph, and S. P. Kinney, *Time Element in Iron Ore Reduction* (Blast-Furnace and Steel Plant, May 1924, vol. 12, pp. 246-250, 254). A further instalment of the authors' report on their investigations with the U.S. Bureau of Mines experimental blast-furnaces gives the results of a study of the time required for the reduction of iron ore in the blast-furnace.

P. H. Royster, T. L. Joseph, and S. P. Kinney, *Influence of Ore Size on Reduction* (Blast-Furnace and Steel Plant, June 1924, vol. 12,

pp. 274-280). Tests were performed with ore graded to medium size,  $\frac{1}{2} \times \frac{3}{8} \times \frac{1}{4}$  inch; lump ore,  $1\frac{1}{2} \times 1 \times \frac{1}{2}$  inch; and fine ore passed through a screen with  $\frac{1}{8}$  inch opening. The coke and limestone remained unchanged. With the ore of medium size the furnace operated smoothly. Throughout the test with lump ore the furnace had all the signs of a cold hearth; and the fine ore reached the tuyeres in an incompletely reduced state, which caused a clogging effect in the hearth and in the combustion zone. Other experiments were made which showed the advantage of uniform grading of the ore in securing uniformity in the quality of the product.

T. L. Joseph, *Effect of Sulphur on Blast-Furnace Process* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1924). The author deals with the distribution of sulphur in blast-furnace materials and indicates how its presence alters the composition, quantity, and critical temperature of the slag, and the relation between these factors, fuel economy, and the cost of the iron. The sulphur distribution per ton of iron in charcoal and coke practice is tabulated. Sulphur balances calculated from operating data covering thirty-five coke furnaces indicate that approximately 92 per cent. of the total sulphur charged enters with the coke, 7 per cent. with the ore, and 1 per cent. with the limestone. Most of the sulphur is carried from the furnace by means of the slag, the total amount eliminated being the product of the slag volume and the percentage of sulphur it contains. Additional sulphur in the charge must be eliminated either by increasing the percentage of sulphur in the slag or the quantity of slag. From relations found between slag volume and coke consumption and sulphur in the coke and slag volume, curves were prepared showing the relative value of blast-furnace coke as its sulphur content varies from 1 per cent.

B. Stoughton, *The Smelting of Magnetite* (Monthly Bulletin of the Canadian Institute of Mining and Metallurgy, September 1924, No. 149, pp. 594-596). The use of magnetite ore in the blast-furnace requires special furnace design, involving slower work, reduced height of bosh, and reduced batter of inwalls. The velocity of the blast must also be greater, which means less tuyere area per thousand cubic feet of blast volume per minute. It is also necessary that the coke be more uniformly graded and considerably larger than the size of coke required for smelting hæmatite ores.

J. Kent Smith, *Nitrogen in Iron* (Foundry Trade Journal, May 15, 1924, vol. 29, pp. 403-405). The influence of titanium, vanadium, and zirconium on the elimination of nitrogen in iron is discussed. The combination of nitrogen and iron is effected in the blast-furnace by means of a "cyanogen reaction." In the light of our present knowledge no precise pronouncement as to the nature and mechanism is possible. But it has been recorded by observers that blast-furnaces, when producing in their hot zones undue quantities of potassium cyanide, produce pig iron which converts to steel of poor hot-working and



mechanical qualities. The logical course to pursue is to avoid the cause of nitrogenisation or, in other words, entirely to preclude "cyanogen reaction." To do this the avoidance of intense temperature at any particular zone in the initial reduction of metallic iron from its mineral source is paramount. The author contends that the most important attribute of iron produced by low temperature reduction would be found in its freedom from nitrides.

J. Seigle, *The Necessary Relationship between the Percentages of Constituent Gases* (Revue Universelle des Mines, April 15, 1923, vol. 2, pp. 96-98). A knowledge of the reactions taking place in the blast-furnace supplies data for checking the analyses of the resulting gases, as the relationship between the various constituents must be a constant and invariable one. The volume of the gaseous products and of the air blown (the blast) per kilogramme of carbon are functions of the percentages; for example in the case of pure carbon, with dry or moist blast, and the volumes being referred to 0° C. and standard pressure:

$$\text{Gas produced} = \frac{186}{\% \text{ of CO}_2 + \% \text{ of CO}} \text{ in cubic metres.}$$

$$\text{Air blown} = \text{gas produced} \times \frac{79}{\% \text{ of N}} \text{ in cubic metres.}$$

The potential heat, per cubic metre of the gas, can be calculated from the percentages of CO and H and deducted from the potential heat given by 1 kilogramme of carbon. Very often heat balances are drawn up corresponding with percentages of CO<sub>2</sub>, CO, and H, which cannot exist, and volumes of blast, and of resulting gases, which correspond with no actual facts, are derived therefrom. A knowledge of the necessary and inevitable relations which exist will serve to obviate errors from such sources.

J. Seigle, *Composition of Blast-Furnace Gas* (Comptes Rendus, 1924, vol. 178, pp. 1426-1429). Calculations are given to show the effect on the composition of the blast-furnace waste gases of using dried blast, blast enriched with oxygen, and blast consisting of pure oxygen. The possible proportions of carbon dioxide and monoxide are graphically represented, and the maximum volume of oxygen burnt per kilogramme of carbon is calculated.

A. Pavloff, *The Remelting in Blast-Furnaces of Steel Scrap and Slags* (Revue de Métallurgie, Mémoires, September 1923, vol. 20, pp. 613-619). An account of the practice resorted to in Russia during the war to increase the production of pig iron. The means to be employed were discussed in the winter of 1916 at a conference held at Kharkoff. At this time the amount of shell steel scrap which had accumulated was considerable, and the utilisation of this scrap constituted almost a matter of State importance. At Koulebaky large quantities of steel turnings mixed with rich slags were smelted in charcoal furnaces, with the help of small proportions of ore, which were introduced more



as fluxes than for any other purpose. A table is given showing the dimensions of the blast-furnaces employed, and details are given of the blast temperature and pressure and the composition of the burden, and analyses of the materials used, the slags, and the pig iron produced. In the result it was found that the production could be doubled with only the normal charcoal consumption necessary when an all-raine charge was used. A high grade acid open-hearth pig iron was produced, but the practice was found to result in rapid destruction of the lining. The methods employed to remedy this, and the nature of the lining which was subsequently substituted with successful results, are likewise described.

S. Brull, *Use of Natural Phosphates in the Iron and Steel Industry* (Technique Moderne, 1924, vol. 17, pp. 138-143). The author discusses the relative merits and effects of the use of rich phosphate and of phosphated limestone in the blast-furnace.

T. T. Read, *Composition of Raw Materials and Pig Iron Costs* (Paper read before the American Iron and Steel Institute, May 1924). The author discusses the effect which the composition of the raw materials used has on the costs of pig iron manufacture, with special reference to American practice.

H. Le Chatelier and B. Bogitch, *Formation of Bears in Shaft-Furnaces* (Comptes Rendus, March 31, 1924; Génie Civil, April 12, 1924, vol. 84, pp. 360-361). An account of the conditions under which so-called bears are formed in the hearths of shaft-furnaces.

**Mixers.**—J. Welter, *Thermal Investigation of a Metal Mixer* (Chaleur et Industrie, March 1924, vol. 5, pp. 105-109). A description of a research carried out early in 1922 at the Hagondange Steelworks, as part of a general study of heat losses from the instant where pig iron is run out of the blast-furnace, to its delivery at the converter. The pig iron in question was basic, and the metal mixer was a hydraulically tipping cylindrical vessel of 1100 tons capacity. The heat balance established was based upon the known temperature of the molten metal, before and after passing through the mixer. The pig ladles were of 12 to 15 tons capacity and travelled distances varying from 300 to 800 metres from the furnaces to the mixer, into which they were poured, after skimming the slag and being hoisted a vertical distance of about 15 metres. The ladles were weighed before and after pouring. The metal withdrawn from the mixer, which was fired by unheated coke-oven gases, was similarly checked and weighed. The gas supply was metered. The mixer lining was silica brick, covered with magnesia brick, and the average supply of pig iron to the mixer was 600 to 800 tons per 24-hour day. The mixer was only full on Mondays, when the Sunday charges had been stored up. The investigations were, in order to equalise the disturbing effects of week-ends, taken over a continuous period of 59 days. Tables and curves of the results are given, all the chemically reactive agents being duly taken into consideration. The

average temperature at which the molten metal was poured into the mixer was  $1353^{\circ}\text{C}.$ , and that of the metal poured out of the mixer for use in the steel converters  $1278^{\circ}\text{C}.$ , giving an overall temperature loss of  $75^{\circ}\text{C}.$  These figures agree well with the theoretical requirements established by the balance sheet and show the mixer to be not inefficient.

**Enriched Blast.**—M. Derclaye, *Considerations relative to the Gruner Constant for Blast-Furnaces blown with Super-Oxygenated Air* (Revue de Métallurgie, December 1923, vol. 20, pp. 830-835). A diagram and formulae are given, based upon the formulæ given by J. Seigle, from which the following conclusions are derived respecting the use of oxygenated blast. From a practical point of view there will be nothing to gain in having more than 26 per cent. of oxygen present in the blast : with this amount, an economy corresponding with 100 kilogrammes of pure carbon could be obtained. Pure oxygen introduced with the blast does not increase the number of calories available, as is the case with ordinary hot blast and with dry blast, and the economy resulting from the addition of a little oxygen is to be explained by the fact that the  $\text{CO}_2/\text{CO}$  ratio is raised to the highest point compatible with chemical equilibrium, that is to say to the upper limit of the effective utilisation of the carbon. The potential heat of the gases is reduced, and this diminution added to the reduced sensible heat resulting from the impoverishment of the gas by nitrogen suffices to explain the gain. The addition of a small amount of oxygen to the blast, although tending to appreciable fuel economy, will have, as its predominant effect, an increase in the furnace productivity, and it is from this point of view that experiments in super-oxygenation of the blast should be undertaken.

J. Seigle, *The Use of More or Less Super-Oxygenated Blast* (Revue de Métallurgie, May 1924, vol. 21, pp. 260-264). A criticism of the results arrived at by Derclaye. The use of the Gruner equation in calculations relative to the possible economies to be effected by the use of oxygen cannot unfortunately be used *a priori*; it has to be established individually by direct experiment in each case, and it is not possible in practice to extrapolate from the values of the Gruner ratio, derived from the use of definite percentages of oxygen, the results which would accrue when using higher percentages. While it is possible, arithmetically, to obtain figures, they do not necessarily bear any relation to actual results in practice.

R. Schenck, *The Application of Oxygen and Enriched Blast in the Smelting of Iron Ore* (Stahl und Eisen, May 8, 1924, vol. 44, pp. 521-526). The author considers the possibilities of employing pure oxygen for the blowing of blast-furnaces. The use of oxygen alone, however, is impracticable, on account of the very high temperatures which would result. No ordinary refractory bricks could withstand such temperatures, and the greatly accelerated reactions and speed of reduction

would produce disturbances which destroy the regularity of the smelting process. By using a suitable mixture of oxygen and blast-furnace gases, however, the temperature could be controlled within any desired range. The cost of production of pure oxygen by liquefaction processes has been brought down to a figure that places the use of oxygen well within the bounds of commercial possibilities. In the United States and in France oxygen of 99 per cent. purity has already been produced at a cost of about a farthing per cubic metre, or, say, 15s. per ton, and the advantages of employing such oxygen mixed with blast-furnace gas are very apparent. It would no longer be necessary to heat the blast, consequently all stoves could be abolished, and on account of the much-reduced volume of the blast the blowing-engine capacity could be greatly reduced. The chief advantage would be the total elimination of nitrogen from the blast, leading to a great economy of heat and a corresponding reduction in fuel consumption. Actual experiments with oxygen mixed with blast-furnace gas are not yet reported, but trials in America have shown that by using atmospheric air enriched with oxygen up to 30 per cent. by volume, it is not necessary to heat the blast, and the output is increased by 18 per cent., with a considerable saving of coke. The adoption of oxygen mixed with blast-furnace gas and the elimination of atmospheric air would probably lead to extensive modifications in blast-furnace design.

F. W. Davis, *Some Applications of Oxygen to Ferrous Metallurgy* (Iron and Steel Engineer, 1924, vol. 1, pp. 339-351). The author summarises the findings of the United States Bureau of Mines on the use of oxygen-enriched air in metallurgical processes. It is shown that oxygen could be produced in quantity at \$3 per ton, and that its use would effect great economies in iron and steel manufacture.

**Cleaning of Blast-Furnace Gas.**—R. Durrer, *Recent Results in the Electric Cleaning of Blast-Furnace Gases* (Stahl und Eisen, July 10, 1924, vol. 44, pp. 809-812). An experimental electric gas-cleaning plant has been installed at the Dillingen blast-furnaces in the Saar district, and the results are now reported. The system is the same as that lately reported at the Rheinische Stahlwerke, namely, the Zschocke system as constructed by the Electric Gas Cleaning Company at Kaiserslautern. The plant is constructed to deal with 10,000 cubic metres per hour, and working at normal capacity the gas was cleaned from 2·5 grammes of dust per cubic metre down to 0·005 gramme. When overloaded by 26 per cent. the average degree of cleanliness was still maintained at 0·003 to 0·005 gramme. At 59 per cent. overload the cleanliness fell to 0·014 gramme, and at 82 per cent. overload it averaged 0·019 gramme. The power consumption is given as  $\frac{1}{2}$  kilowatt-hour per 1000 cubic metres in the experimental plant, which figure would doubtless be improved upon in a large plant. The economy is, in fact, so great compared with other systems that it is prophesied that the electric system will shortly displace all others. The installation is illustrated.

J. Dreher, *Tests on an Electric Gas-Cleaning Plant at the Lübeck Ironworks* (Stahl und Eisen, July 24, 1924, pp. 873-879). Since 1921 an electric gas-cleaning plant of the Lurgi type has been in operation at the Lübeck blast-furnaces. Trials carried out under varying conditions show that the degree of cleanliness attained in the gas is from 98 to 99.9 per cent., and it is estimated that the saving in current compared with the wet-cleaning process is 73 per cent. The quantity of gas passing through the cleaner per hour was 2500 to 3200 cubic metres. The economy of the plant in water and power greatly exceeds that of any other system.

N. H. Gellert, *Electrical Cleaning of Blast-Furnace Gases* (Blast-Furnace and Steel Plant, September 1924, vol. 12, pp. 423-426). Progress in the practice of blast-furnace gas cleaning is reviewed, and the merits of the dry and the wet cleaning processes are compared, and to the advantage of the dry method. The electric method of cleaning is superseding other dry methods, on account of its low operation costs and the little attention that it requires.

N. H. Gellert, *Electric Cleaning of Blast-Furnace Gas* (Iron Age, August 28, 1924, vol. 114, pp. 502-503).

G. M. Hohl, *The Cleaning of Blast-Furnace Gas* (Paper read before the American Iron and Steel Institute, May 1924). The paper contains short descriptions of various types of blast-furnace gas cleaners and washers.

J. F. Barkley, *Flow of Blast-Furnace Gas in Large Mains* (Iron Age, June 19, 1924, vol. 113, pp. 1811, 1825).

**Electric Smelting of Iron Ore.**—F. Hodson and M. Sem, *New Norwegian Pig Iron Furnace* (Iron Age, May 29, 1924, vol. 113, pp. 1585). Particulars are given of the operation of the new electric smelting furnace at the Tinfos Works, Norway. During the running of the furnace all kinds of ore were used, and both charcoal and coke were used as a reducing agent. The furnace was of the pit type, with vertical electrodes. The running was divided into three periods. During the first period of the test the furnace was run as an open pit furnace, with one top Soderberg electrode and one bottom electrode. In the second period the furnace was provided with two top electrodes in series. During the third and most successful period of test the furnace was closed with a brick roof provided with a charging shaft around the electrodes, and the gases were collected by pipes. Brief particulars are also included of a new process of ore reduction, which is applicable to smelting both ferrous and non ferrous ores, and consists in making up the whole of the ore to be reduced in the form of composite Soderberg continuous electrodes. The ore is mixed with carbon in the form of pitch or tar, current is passed through the electrodes, and the resistance of such electrodes to the passage of current drives off volatile gases which can be collected and applied to the reduction of the ore. The first product in the lower zone of the electrode is a pure carbon-free sponge. As the electrode reaches the arcing zone of the



furnace the iron sponge becomes molten iron, with low carbon content. Practically all the heat put into the process is usefully employed, and the actual heat generated in the electrode can be readily controlled and regulated.

R. Durrer, *Waste Gas Economy in the Electric Smelting of Iron Ore* (Stahl und Eisen, June 26, 1924, vol. 44, pp. 748-750). Complete data concerning the working of the electric furnaces at Domnarfvet are given, with analyses of the Swedish ores used, of the slag and of the waste gas, and the composition of the burden. It is suggested that greater economy in the smelting process would result if the whole of the waste gases were circulated through the shaft of the furnace instead of only a portion as at present.

**Manufacture of Ferro-Alloys.**—W. M. Mitchell, *Chromium: Its Uses and Its Alloys* (Forging, Stamping, Heat-Treating, May, June 1924, vol. 10, pp. 199-202, 235-238; Blast-Furnace and Steel Plant, August 1924, vol. 12, pp. 372-375 *et seq.*). The sources of chromite are mentioned, and the uses of chromium in industry generally are described, with special reference to its use in the steel industry for the manufacture of alloy steels, and heat and corrosion-resisting alloys. Incidentally, a description of the process of the manufacture of ferro-chromium in the electric furnace is given. Chromite is smelted with anthracite coal at a high temperature, which reduces the chromite directly to a 6 to 8 per cent. carbon ferro-chromium at one operation. To reduce the carbon further the alloy is again melted in another electric furnace with a slag of chromite, lime, and fluorspar. In this way the carbon may be reduced to 0.50 or even 0.25 per cent., the chromium content remaining practically without change. Various reduction processes have been patented for the further elimination of carbon, and ferro-chromium can now be produced with 0.10 per cent. of carbon or less, but the cost of refining is still very considerable.

R. W. Smith, *Geology and Utilisation of Tennessee Phosphate Rock* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1924). A brief history of the phosphate industry of Tennessee is given, and the distribution and origin of the phosphate rocks are described. Particulars of the method of mining, treatment, and uses are included. There is an increasing demand for high-grade lump rock for use by steel plants in the United States. The entire production of ferro-phosphorus in the United States is from two furnaces—the Rochdale furnace at Rochdale, Tennessee, and the furnace of the Federal Phosphorus Co., Anniston, Alabama. The Rochdale furnace is a 55-foot stack equipped with four stoves. Coke, lump phosphate rock, siliceous brown iron ore, mill cinder, and limestone are the materials charged. The Federal Phosphorus Co. operates an electric furnace.

**Iron Industries of Various Countries.**—*Iron Ore Supplies* (Mining Journal, September 13, 1924, vol. 146, p. 728). The present position



of the iron ore mining industry in the Cleveland district is commented on, and figures are given showing the decline in the production of ironstone from 1910 to 1923. The Cleveland blast-furnaces are becoming more and more dependent upon foreign ore supplies.

E. C. Kreutzberg, *Orange County Ironmaking* (Iron Trade Review, July 17, 31, 1924, vol. 75, pp. 157-160, 284-288). The author gives an interesting account of the history of the iron industry of Orange County, New York State. This county once was an important iron centre, and for a considerable period was the principal producing district in the State. The industry started prior to 1750. The last furnace in blast in the county was the Sterling Stack, which was blown out in 1891. The Sterling Ironworks supplied the anchors for the first ships of war that carried the American flag, and particularly for the United States Frigate *Constitution*. It also produced the great iron chain which was placed across the Hudson River at West Point to hold back British vessels. During the revolution the Sterling Ironworks was an important source of munitions.

O. Wehrheim, *Equipment and Lay-out of Blast-Furnace Works in the United States* (Stahl und Eisen, August 21, September 4, 11, 18, 1924, vol. 44, pp. 1006-1012, 1074-1080, 1105-1112, 1138-1145). The serial consists of a report of the Blast-Furnace Committee of the Verein Deutscher Eisenhüttenleute on American blast-furnace plant and its general arrangement, design, and operation.

Martchenko, *The Present State of Metallurgy in Russia* (Revue de Métallurgie, February 1924, vol. 21, pp. 121-126). The Soviet Decree of August 12, 1921, reserved the metal, coal, and mineral industries solely for State exploitation, as industries of prime importance. They are therefore not open to individual enterprise, as is the case in some of the other industries in which State Capitalism, having proved a failure, has been abandoned. This notwithstanding, the metallurgical works draw a large proportion of their raw materials from individualistic rather than State sources, as the State industries are totally incapable of producing materials at economically reasonable prices. In spite of the wealth in coal, in Russia, fuel is everywhere lacking, and most of the iron and steel works can be operated only intermittently. At the blast-furnace plants at Petrovsky and at Hughesovka, however, pig iron is being regularly produced. The production in Central Russia has fallen to 2.8 per cent. of that of 1913; thus, in 1922 only 5,358,000 poods (98,000 metric tons) were produced. Coke is scarce, and has had to be brought from outside sources, even to works which are situated in regions where good coking coal exists. Ore stocks are likewise greatly reduced. All branches of the iron and steel trades languish in proportion. For example, the open-hearth steel output for 1922 was only 4 per cent. of the 1913 output. An edict has been passed forbidding the use of more than 45 per cent. of new pig iron in the open-hearth charge (June 1923). On October 1, 1922, the total stock of open-hearth steel for all Russia was only 135,000 tons.

Statistics are given relative to the production of rolled sections, bars, sheets, &c., and particulars of the wages paid are included. Thus the operatives themselves receive on an average 4·70 gold roubles per month, with a 50 per cent. bonus; while the higher technical staff are paid an average monthly salary of 37·60 gold roubles, and a 30 per cent. bonus. The cost of producing rolled steel is 8 roubles per pood, which corresponds with £36 to £37 per ton, and is approximately eight times as much as the pre-revolution cost.

*Blast-Furnace Plant at Asansol, India* (Iron Age, July 31, 1924, vol. 114, pp. 254-255). A brief illustrated description is given of the blast-furnace plant of the Indian Iron and Steel Co., near Calcutta.

*Completely Modern Indian Furnaces* (Blast-Furnace and Steel Plant, September 1924, vol. 12, pp. 398-400). A brief illustrated description is given of the new blast-furnace plant of the Indian Iron and Steel Company, at Asansol, about 120 miles north-west of Calcutta. The two blast-furnaces were designed by, and constructed under the supervision of, A. G. McKee & Company of Cleveland, Ohio. The most modern mechanical appliances for labour saving have been adopted, notwithstanding low labour costs.

*A Blast-Furnace in New Zealand* (Engineer, June 20, 1924, vol. 137, p. 690). A description is published of a blast-furnace recently put into operation at Onakaka, in the South Island of New Zealand, by the Onakaka Iron and Steel Company. The daily capacity of the furnace is about 30 tons of grey pig iron of good quality. Iron ore deposits said to contain some hundreds of million tons of limonite ore are in the immediate neighbourhood. Limestone beds also occur in close proximity, and both ore and limestone are brought by ropeway a distance of  $1\frac{1}{2}$  mile. Good coking coal is obtainable within economic distance, and sixteen bee-hive ovens have been erected near the furnace. The works are on the coast, and the erection of a wharf is projected so that vessels can lie alongside.

**Pig Iron Specifications.**—*American Government Specify Pig Iron by Rule* (Foundry Trade Journal, July 24, 1924, vol. 30, p. 70). Particulars are given of a specification for foundry pig iron adopted by the American Federal Specifications Board for the use of the Government departments in the purchase of pig iron. Pig iron is classified into four grades of the following composition:

	No. 1. Per Cent.	No. 2. Per Cent.	No. 3. Per Cent.	No. 4. Per Cent.
Silicon . . . . .	2·75-3·25	2·25-2·75	1·75-2·25	1·25-1·75
Sulphur (maximum) . .	0·04	0·05	0·05	0·05
Total carbon (minimum) .	3·40	3·20	3·20	3·20
Manganese . . . . .	0·50-1·00	0·50-1·00	0·50-1·00	0·50-1·00
Phosphorus . . . . .	0·50-0·80	0·50-0·80	0·50-0·80	0·50-0·90

**History of Iron.**—J. N. Friend, *Iron in Antiquity* (Carnegie Scholarship Memoirs, 1923, vol. 12, pp. 219-290). The author traces the history of the use of iron from the earliest ages in all countries. An attempt has been made to direct attention to the more important features of the subject, and the memoir contains much information which has not hitherto been collected together in one monograph.

J. N. Friend and W. E. Thorneycroft, *Examination of Iron from Konarak*. (This Journal, p. 313.)

*One Hundred Years of British Railways* (Engineer, July 4, 11, 18, 25, August 1, 1924, vol. 138, pp. 17, 37-38, 78-79, 108-109, 136-137, &c.). The first of this interesting series of articles gives an historical account of the use of iron for rails of wagon-ways and the gradual development of iron rails for the first railways opened in the United Kingdom.

H. Littlehales, *The Evolution of the Pig* (Foundry Trade Journal, July 24, 1924, vol. 30, pp. 80). The term "bloom" is the earliest known name used for the mass of metal obtained from smelted ore. This name was maintained in use for many centuries, and is mentioned in many documents of the Anglo-Saxon period. In the fifteenth century the bloom had often the alternate name of "sow." In the early part of the sixteenth century, just as the name "sow" had ousted that of "bloom," the term "pig" seems to have become the term used for the lump of iron from the ore. The distinction has often been drawn between sows and pigs that the casting bed consisted of a main channel, with smaller channels on either side, and that after the casting the mass of metal of the main channel was known as the sow, and the castings in the smaller channels as pigs. It is probable that such form of casting was at times adopted, but documentary evidence shows that the name of sow belongs to one period and that of pig properly to another and later period.

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## II.—BLAST-FURNACE SLAGS.

**Function of Slags.**—J. E. Fletcher, *On the Working Slags in Ferrous Processes* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, May 15, 22, 1924, vol. 29, pp. 395-398, 429-432). The author outlines the function of slags in the blast-furnace, cupola, puddling furnaces, Bessemer converters, and open-hearth furnaces. Compositions of typical slags are tabulated.

**Classification of Slags.**—W. G. Imhoff, *Colour Classification of Blast-Furnace Slags* (Blast-Furnace and Steel Plant, August 1924, vol. 12, pp. 362-367). The classification of blast-furnace slags is based on two factors—temperature and slag composition. The temperature may be considered as hot, medium hot, and cold, and a table is given

showing the characteristics of these three types of slag. The temperature indicators are silica, manganese, and iron. A white hot lime slag is low in silica, and as the silicon goes from the iron to the slag as silica, the hearth temperature gradually falls; thus the amount of silica in the slag becomes an indicator of the hearth temperature. As the hearth temperature falls, if there is an appreciable amount of manganese present the slag will show a brown glaze. This is the dividing line between hot and medium hot slags; but manganese will not go into the slag however hot the furnace is if there is very heavy lime in the charge. Iron is the easiest and best temperature indicator, and the two extremes of slag temperature are readily distinguished by the iron present. A hot lean slag has a light green glaze, a cold lean slag is black, and all shades of both are found between the two extremes of temperature. Iron colours slag black, and the degree of temperature for the given slag composition is indicated by the amount of black iron oxide formed.

**Uses of Slag.**—E. H. Lewis, *Iron Portland Cement* (Proceedings of the Cleveland Institution of Engineers, Session 1923-24, No. 4, pp. 139-163). The paper describes tests on iron Portland cement, the results of which show that this material, if properly made, is at least equal to ordinary Portland cement.

A. Guttman, *The Properties of Electrically Manufactured Cement (Electro-Cement) and its Application in the Manufacture of Metallurgical Cements* (Stahl und Eisen, July 3, 10, 1924, vol. 44, pp. 786-794, 815-819). A description is given of Wennerström's method of treating blast-furnace slag in the electric furnace with lime additions, till the proportion of lime equals that in a true Portland cement. The results are given of an analytic and microscopic investigation, and of mechanical tests of electro-cement; also of slag cements and furnace cements made from electro-cements.

A. Guttman and K. Biehl, *Fluorspar as an Ingredient of Blast-Furnace Cement* (Zement, 1924, vol. 13, pp. 48-50, 55-57, 64-65, 76-78, 85-87). The sintering temperature of a ground cement composed of blast-furnace slag and lime is considerably lowered by the addition of fluorspar. The amount which can be safely added is generally about 1 per cent., but it should in no case exceed 3 per cent., otherwise the fluorspar will cause the clinker to disintegrate. No appreciable saving in fuel is effected by adding fluorspar, but the lime combines more freely and a better clinker is produced, which gives a cement of a greater constancy of volume. The time of setting is also reduced.

H. Burchartz, *Slag Sand as Aggregate in Concrete and Ferro-Concrete* (Stahl und Eisen, June 5, 1924, vol. 44, pp. 650-657). The slag sand, produced by granulating blast-furnace slag, is crushed to a size which will pass through a sieve with seven meshes to the centimetre. Concrete of a satisfactory grade can be made by using either light or heavy slag sand as aggregate. The strength of concrete made with light slag sand is slightly lower than that made with natural sand,



but with dense slag sand the strength is at least equal to or may be stronger than that in which natural sand is used.

*Specifications for the Manufacture and Supply of Blast-Furnace Slag as an Addition to Concrete and Ferro-Concrete* (Stahl und Eisen, May 22, 1924, vol. 44, pp. 590-591).

F. Riedel, *New Process for Manufacture of Pipes from Blast-Furnace Slag* (Stahl und Eisen, September 25, 1924, vol. 44, pp. 1173-1174). The Dresler process for the manufacture of bricks from blast-furnace slag without the use of lime or cement as binders has been successfully applied to making pipes. The mould and core are made of sheet steel, and the ground slag is rammed by hand alternately with slag sand in the space between core and mould. These latter can be removed at once, and the pipe is placed in a chamber and exposed for two days to carbon dioxide gas, which is drawn through from one of the stoves with a fan. After such treatment a pipe of 12-inch diameter is strong enough to bear a load of  $2\frac{1}{2}$  tons. The pipes are then coated inside with a wash of cement to make them water-tight.

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### III.—DIRECT PROCESSES.

**Direct Production of Iron.**—*Direct Reduction of Ore* (Iron Trade Review, June 19, 1924, vol. 74, pp. 1635-1636). Preliminary experiments on the low temperature reduction of iron ore by means of a series of rotary kilns have been conducted at a demonstration plant built by the Hornsey Iron Co., Ltd., at Sheepbridge, near Chesterfield. The kilns are each about 5 feet in diameter and 30 feet in length. The first is used for preheating, the second for reduction, and the third for cooling the product. Each cylinder is driven by a separate motor with a variable speed starting-box, which permits rotation at speeds from one revolution in half a minute to one revolution in two minutes. Pulverised coal is employed which makes it possible readily to control the combustion and to maintain constant temperatures. At no point in the process does the temperature rise above  $1050^{\circ}\text{C}$ . The iron product is separated from the gangue by passing over magnetic separators. The product differs physically from that of the blast-furnace, in that it is in a granular form instead of being in the shape of pigs. It also differs chemically in that the iron reclaimed is essentially pure, resembling wrought iron, and is mixed mechanically with varying percentages of the other ingredients of the ore instead of being chemically combined with them. The carbon content is also lower than that of pig iron, but can be controlled within reasonable limits. The Hornsey furnace produces a steel intermediate which may be used to make refined steel or wrought iron. This intermediate product can be handled in the open-hearth, preferably starting with a small bath of molten pig iron, or melted in the electric furnace. The general results obtained from steels made by this process are tabulated, and an axle



temper plain carbon steel made from the Hornsey product alone, using no pig iron or other admixture, is compared with two-standard steels of the same character. The analyses of the principal ores used at Sheepbridge are also given.

A. Groenwall, *Electric Production of Steel directly from Iron Ore* (Teknisk Ukeblad, 1924, vol. 42, pp. 21-22). In the method suggested by the author the ore is ground to pea size and roasted in a rotary kiln. The roasted ore is treated in another kiln, where it is mixed with finely ground coal. The temperature of this kiln is kept at 800° to 900° by means of nichrome resistors placed in the brick lining. From this kiln the materials are charged into an electric shaft furnace and smelted to steel or soft iron. The metal is then refined in an ordinary electric steel furnace, where the composition and quality can be regulated. A plant with a capacity of 10,000 tons per annum is calculated to require: 1600 kilowatts for the reduction furnace, 450 kilowatts for the smelting furnace, and 350 kilowatts for the steel furnace. The fuel and electrode consumption is calculated at 280 kilogrammes of coke and 2 kilogrammes of graphite electrodes per ton of steel. A detailed plan of the suggested plant is included.

E. Fornander, *The Direct Production of Iron* (Chemical and Metallurgical Engineering, June 2, 9, 1924, vol. 30, pp. 864-868, 907-910). A review is given of the more important methods that have been used for the production of wrought iron direct from ore. The processes dealt with are: Chenot, Gurlt, Husgafvel, Wiborgh, Gröndal, Sieurin, Ehrenwerth, Bourcoud, Berglöf, Wiberg, and Basset.

**Electrolytic Production of Iron.**—T. W. S. Hutchins, *Electrolytic Iron* (Paper read before the World Power Conference, July 1924: Iron and Coal Trades Review, July 18, 1924, vol. 109, pp. 117-118). The author deals with those processes which have for their object the commercial production of electrolytic iron in tubes, sheets, &c. Such systems might be divided substantially into three classes:

(1) Processes wherein the anodes are formed (cast or shaped) and are soluble, so that the iron deposited from the electrolyte is replaced by solution of these anodes, together with the iron in the absorbers or recuperators (French process).

(2) Processes wherein the anodes are shaped, but insoluble, so that the whole of the iron deposited from the electrolyte is replaced by solution of the iron in the recuperators (U.S.A. process).

(3) Processes wherein the anodes are soluble, but unformed, so that the iron deposited from the electrolyte is replaced by solution of these anodes, together with the iron in the recuperators (British process).

The nature of the defects in electrolytic iron is discussed, and particulars of the cost of production are included. The author also discussed the results obtained from tests upon a number of tubes produced under varying conditions as to current density, electrolyte concentration, acidity, temperature, and filtering mediums.

## FOUNDRY PRACTICE.

**General Foundry Practice.**—A. Wagner, *The Dimensions of Cupola Furnaces, particularly in Relation to the Weight of the Charges, Rate of Melting, and Coke Consumption* (Stahl und Eisen, May 29, 1924, vol. 44, pp. 617–622). A series of experiments was undertaken on three cupolas, one of which was equipped with a forehearth and had a diameter 32 inches at the tuyere level, with a rate of melting of 3 to 3·4 tons per hour. The second cupola was 28 inches diameter, with two rows of tuyeres and a rate of melting of 2·3 to 2·6 tons per hour. Both of these cupolas were charged mechanically. The third was a small hand-charged cupola of 19 inches diameter. The larger the size of the cupola the less efficient it becomes in point of fuel consumption, and the heat-balance is accordingly less good. The rate of melting is influenced by the weight of the coke and iron charged, the operation proceeding more rapidly the lighter the charge. Considerable advantage is derived from the use of a forehearth, as the melting losses are much less on account of less frequent slagging off.

Werner, *German Foundry Practice* (Foundry Trade Journal, September 11, 1924, vol. 30, pp. 229–232). In his address delivered at the International Foundry Trades Exhibition at Birmingham, the author discusses recent advances in foundry practice in Germany, and gives particulars of operating results with the Schurmann cupola.

E. Ronceray, *The Modern Evolution of the Foundry* (Revue de Métallurgie, February, March 1924, vol. 21, pp. 112–120, 183–194). A continuation of the account of recent progress in foundry equipment and methods (see abstract, Journal of the Iron and Steel Institute, 1924, No. I. p. 554). The first instalment deals with moulding and casting. The function of the sinking head in securing sound castings is discussed. Experience is not favourable to its use. Casting in chills and mechanical moulding are also dealt with. In the second instalment the materials and binders for cores are discussed, and a section is devoted to a consideration of the storing and mixing of foundry sands. Finally, the lay-out of the foundry is dealt with, and a short section is devoted to technical education so far as it bears upon foundry work.

A. Marks, *The Manufacture of Pearlitic Cast Iron for High Temperature Engines* (Foundry Trade Journal, May 15, 1924, vol. 29, pp. 406–408). The author describes his experiments in the production of pearlitic cast iron in the cupola, with a view to obtaining the strongest material possible for the manufacture of castings subjected

to high temperature. The production of pearlitic cast iron in practice depends upon the following factors : (1) Correct adjustment of mixture for ferrite, silicon, and graphite—a combined carbon in the region of 0·8 per cent. ; (2) the use of low silicon suitably proportioned to the casting thicknesses and temperatures ; and (3) quick cooling of the metal through critical ranges and subsequent prolonged low temperature annealing in the mould.

H. Van Aarst, *Economical Melting with Cupolas* (Paper read before the Institute of British Foundrymen : Foundry Trade Journal, June 19, 1924, vol. 29, pp. 522–524). The author discusses the different factors influencing the melting process, with special reference to fuel economy.

A. W. Bryant, *Melts Iron in Twin Furnaces* (Foundry, July 15, 1924, vol. 52, pp. 556–559). At an American foundry two electric furnaces are in operation for supplying small heats of iron at regular intervals. The furnaces, each of  $1\frac{1}{2}$  ton capacity, are mounted on a turntable, one set of electrodes doing duty for the two furnaces. When one furnace is ready for pouring the electrodes are raised clear of the furnace and the turntable is swung round, so that the hot furnace is over the pouring pit and the cold furnace is in line with the electrodes. Only three minutes elapse from the time the power is taken off one furnace until it is started again in the other furnace.

L. J. Barton, *Electric Furnace Iron from the Manager's Standpoint* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 148–153). The costs of melting iron in the electric furnace for the production of castings are analysed.

J. A. Holden, *Metallurgical Control in the Iron Foundry* (Foundry Trade Journal, September 4, 1924, vol. 30, pp. 207–208). Metallurgical control of foundry mixtures for the production of light and heavy castings is dealt with, and typical examples are given.

H. H. Shepherd, *Notes on Combined Iron and Steel* (Metal Industry, June 13, 1924, vol. 24, pp. 577–578, 588). The uses, composition, and properties of combined iron and steel are briefly dealt with.

B. Osann, *Calculation of Foundry Mixtures* (Giesserei Zeitung, August 1, 1924, vol. 21, pp. 317–319). A plan is set out according to which foundry mixtures can best be calculated, and an example is given of the calculation of mixtures to produce castings of a given composition.

G. A. Drysdale, *Simplifying Cupola Mixtures* (Foundry, June 1, 1924, vol. 52, pp. 433–434). A number of selected cupola mixtures for machinery castings is tabulated. The results of tests on test-bars from these mixtures are included.

C. Brunelli, *The Filtration of Cast Iron* (Foundry Trade Journal, October 2, 1924, vol. 30, pp. 283–286). The author advocates the use of filter grates to prevent the introduction of impurities in castings. With the object of separating the gases from the metal by breaking this up away from contact with the air before passing it into the mould,

the author has devised four types of filter grates. One type is designed to supply a good flow of well-filtered metal, so as to avoid ingotism at distant points of a casting, and at the same time control the heat distribution in such castings.

T. W. Barley, *A Comparison of Gas and Coke-Fired Drying Stoves* (Paper read before the Refractory Materials Section of the Ceramic Society : Engineering, September 26, 1924, vol. 118, pp. 460-461). The costs of drying moulds and cores in gas-fired stoves and coke-fired stoves are compared, the particulars being obtained from actual practice with such stoves at the steelworks of Edgar Allen & Co., Sheffield. It is shown that the economy of the gas-fired stove is much superior to that of the coke-fired stove. A description is included of the construction and operation of the Huttenes coke-fired air-blown furnace

B. Shaw and J. Edgar, *Making Propellers* (Foundry Trade Journal, September 25, 1924, vol. 30, pp. 272-273). The authors describe the pattern-making and moulding practice usually adopted in British foundries for the production of propellers.

A. Sutcliffe, *Dry Sand and Loam Moulding* (Paper read before the Institute of British Foundrymen : Foundry Trade Journal, August 21, 1924, vol. 30, pp. 153-154).

R. J. Anderson and M. E. Boyd, *The Production of Castings in Permanent Moulds* (Paper read before the Institute of British Foundrymen : Foundry Trade Journal, June 5, 12, 1924, vol. 29, pp. 464-468, 477-485). The production of castings in permanent moulds is discussed in a general way, and the applications and limitations of the process to both ferrous and non-ferrous castings are pointed out. The history of the permanent mould process is traced, and it is shown that permanent types of moulds, including stone and bronze moulds, were used as long ago as 3000 B.C. Typical examples of such old moulds are shown. It is indicated that there are five separate and distinct casting processes involving the use of permanent or metallic moulds—namely, (1) die-casting, (2) slush casting, (3) Cothias casting, (4) centrifugal casting, and (5) permanent mould casting. These different casting processes are defined, and the first four are discussed briefly, and then compared with the true permanent moulding process, which is the counterpart of sand-casting. The general principles of the permanent mould process are discussed, and a typical mould is described as illustrative of these principles. The question of materials employed for making moulds and cores is dealt with, grey cast iron being used largely for the mould body proper, while both metallic cores and sand cores are employed. The growth and distortion of grey cast iron moulds in service, and the use of refractory linings and coatings are discussed. The various types of alloys used commercially for casting in permanent moulds are considered, and the types of castings made in these alloys are described. A selected bibliography of literature on the use of metallic moulds is appended to the paper.

O. Smalley, *Cylinder Castings* (Transactions of the North-East



Coast Institution of Engineers and Shipbuilders. 1923-24, vol. 40, pp. 355-392). The author discusses the cause and elimination of the commoner defects encountered in the manufacture of cylinder castings.

F. H. Hurren, *Cast Iron in Motor-Car Construction* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, May 22, 1924, vol. 29, pp. 423-426). The most important use of cast iron for motor-car construction is for the cylinder. The cylinder and head are sometimes cast in one piece, but modern practice is to make separate castings for the cylinder head and cylinder body. Other parts where cast iron is utilised are the fly-wheel, clutch plate, clutch cover, exhaust branch, certain chain wheels on the timing gear, brake shoes, liners for brake drums, bearing carriers, and small distance pieces and cover plates. The mechanical test which can be most usefully applied to motor cylinders is the Brinell test. The author's practice is to cast on all cylinders a small test-piece of standardised dimensions, which is rammed up and dried as an integral part of the mould. To some extent aluminium is displacing cast iron for pistons. The main factors in the production of the various parts are noted, and a general outline is given of the cupola practice.

P. Dwyer, *Moulds Large Iron Gear Cases* (Foundry, August 15, 1924, vol. 52, pp. 623-627, 652). The author gives a detailed description of the moulding practice involved in the production of large iron gear cases.

P. Dwyer, *Pumps made in Quantities* (Foundry, June 1, 1924, vol. 52, pp. 417-423, 432). The methods of moulding and casting hand-pumps as practised at a large American foundry are described and illustrated. The mixtures for cupolas are made up entirely from pig iron, selected steel scrap, and returned scrap from the foundry itself. All the light castings made in greensand moulds are poured from soft iron with a silicon content of 2.40 per cent. Medium weight and heavy castings made in green and dry sand moulds are poured from a mixture in which the silicon varies from 1.50 to 2.00 per cent. The castings designed for high pressure work are poured from a semi-steel mixture in which the silicon content does not exceed 1.00 per cent.

P. Dwyer, *Moulding Special Pipe Shapes* (Foundry, May 15, 1924, vol. 52, pp. 373-378). An illustrated description is given of the methods and equipment used at the plant of the Pittsburg Valve Foundry and Construction Co., for the production of large valves and special pipe shapes.

P. Dwyer, *Make Wheels and Brake Shoes* (Foundry, September 15, 1924, vol. 52, pp. 707-712, 729). An illustrated account is given of the methods of producing car wheels and brake shoes at an American foundry.

H. R. Simonds, *Making Textile Machine Parts* (Foundry, July 15, 1924, vol. 52, pp. 537-541). The types of castings used in the production of machinery for the textile industry are described. Complicated parts are of grey iron and malleable castings.



R. A. R. Cole, *The Manufacture of Chilled Iron Rolls* (Paper read before the Midland Branch of the Institution of Mechanical Engineers: Machinery, July 24, 1924, vol. 24, pp. 533-534).

*Movable Moulding Machine for Large Work* (Iron Age, July 31, 1924, vol. 114, pp. 247-249). An illustrated description is given of a large Beardsley and Piper sand-slinging machine in operation at an American foundry. The machine is capable of mixing and ramming about 200 tons of sand per day.

J. McClelland, *Moulding Machines* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, July 17, 1924, vol. 30, pp. 57-60). Various types of moulding machines are described and illustrated.

**Manufacture of Synthetic Iron.**—C. E. Sims, C. E. Williams, and B. M. Larsen, *Manufacture of Synthetic Foundry Iron in the Electric Furnace* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 154-170). According to the authors the production of synthetic foundry iron in the cupola is impracticable, owing to the inability to obtain, consistently, a metal of high carbon content, and to the excessive slagging and its consequent troubles, the large proportion of coke required and the consequent introduction of a relatively large amount of sulphur, and the large loss of silicon by oxidation. In the electric furnace, carbon contents of from 3.5 to 4.0 per cent. can be easily obtained. Practically any class of ferrous scrap can be used, which may be in the form of fine turnings or borings, or heavy sections. The best carburising materials are artificial electrode or resistor carbon, petroleum coke, gas-retort carbon, and pitch coke. Ferro-silicon or high silicon iron are best for introducing silicon, although silicon carbide, in the form of "firesand," has proved both cheap and effective, and is also valuable as a carburiser. Any alloy of manganese and iron is satisfactory for the introduction of manganese. If desulphurisation is required, either lime or limestone mixed with fluorspar should be used. The use of silica in the slag must be avoided to obtain rapid introduction of carbon. The electric furnace need not be of a specialised type, but of standard design that can be used interchangeably for iron and steel melting. The method of operation is described in the paper.

**Semi-Steel.**—G. W. Gilderman, *The Making of Semi-Steel Casting* (Foundry Trade Journal, July 17, 1924, vol. 30, pp. 44-45). A general description of the methods used in the production of semi-steel castings.

G. A. Drysdale, *White Iron for Grinder Discs* (Foundry, August 1, 1924, vol. 52, pp. 591-592). In the production of white iron suitable for grinder discs, the physical properties are controlled to a great extent by the percentages of steel scrap used in the mixture. Suitable cupola mixtures are tabulated.

**Steel Foundry Practice.**—J. Grennan, *Melting Steel in a Cupola* (Paper read before the American Foundrymen's Association, October 1924). The author gives the result of further experiments to determine the manner in which steel melts in a cupola. A series of holes was cut through the side of the cupola in order to observe the process of melting, and to remove pieces of stock for examination.

W. H. Woodhall, *The Manufacture of American Steel Castings* (Foundry Trade Journal, May 15, 1924, vol. 29, pp. 399-401). The author outlines American practice in the manufacture of steel castings. It is recognised throughout the United States that the acid open-hearth is, in most cases, the most suitable process for the production of castings.

L. J. Barton, *Nine Tons in a 3-Ton Furnace* (Foundry, May 15, 1924, vol. 52, pp. 401-403; Iron Trade Review, June 5, 1924, vol. 74, pp. 1493-1495). By minor alterations in the design of a 3-ton electric furnace, its capacity was increased to melt 9 tons of metal for the production of a large gear wheel. The rear or operating door was banked up about 10 inches with a cement made of white sand and sodium silicate. The log of the heat is given.

L. J. Barton, *Refining Metals Electrically* (Foundry, June 1, 15, July 1, 15, August 1, 15, September 1, 15, 1924, vol. 52, pp. 427-432, 460-462, 506-509, 542-547, 606-610, 640-642, 671-674, 726-729). A series of articles describing electric furnace practice, with special reference to foundry work. In the earlier chapters the electric furnace is compared with other methods of producing steel for castings, and the factors governing the selection of electric furnaces are discussed.

E. R. Young, *Designing Steel Castings* (Machinery, July 17, 1924, vol. 24, pp. 501-503). The author discusses various problems encountered in the production of steel castings.

F. Grotts, *Broadening the Field for Steel Castings through the Use of Alloys and Heat Treatment* (Paper read before the American Foundrymen's Association, October 1924). The author discusses the possibilities in the use of alloy steel castings. The alloying elements generally used are chromium and nickel, and in some cases vanadium and molybdenum. The best heat treatment consists in single and double annealing and quenching and drawing. Carbon steels are also discussed in relation to their uses and physical properties.

P. Dwyer, *Valve Castings Made in Steel* (Foundry, August 1, 1924, vol. 52, pp. 579-583). The practice at the plant of the Pittsburgh Valve, Foundry and Construction Co., for the production of valves, is described and illustrated. The steel for the castings is melted in an acid electric furnace.

H. V. Fell, *Production of a Large Steel Casting* (Foundry Trade Journal, August 7, 1924, vol. 30, pp. 114-116). An illustrated description of the operations involved in the moulding of a large steel casting.

*Cast Large Steel Hawse Pipe* (Foundry, May 15, 1924, vol. 52,

pp. 381-384). An illustrated description is given of the method of moulding large steel hawse pipes for the s.s. *Leviathan*. The original hawse pipes were of cast iron, and became unserviceable owing to the heavy duty to which they were subjected. Steel for the castings was melted in an acid open-hearth furnace, the analysis of the steel being: carbon 0.28, manganese 0.57, phosphorus 0.046, sulphur 0.037, silicon 0.29 per cent.

**Moulding Sands.**—A. Rhydderch, *Moulding Sands for Steel Castings* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, May 29, June 5, 1924, vol. 29, pp. 445-448, 460-463). The properties, tests, and preparation of moulding sands used in the production of steel castings, of light, medium, and heavy sections, are discussed. Sands with a large amount of bonding material deteriorate much more rapidly on heating above 100° C. than those with a small amount of bond, and naturally bonded sands show this behaviour in a very pronounced manner. Further, those with a fireclay bond will stand a great deal more fire than those with a natural low bond. For the fixing of temperatures for drying ordinary moulds of naturally bonded sand or synthetic sands, it is not advisable to go beyond 205° C. except in special circumstances, where the mould has to contract under the action of the heat. The rate of drying depends upon the mass of sand to be dried.

H. B. Hanley, *The Bonding Substance of Moulding Sands* (Bulletin of the American Foundrymen's Association, April 1924, pp. 6-10). Chemical analyses of the bonding substance of typical American moulding sands are tabulated, and the chemical and physical properties of bonding substances are discussed.

*Tentatively Adopted Methods of Tests and Résumé of Activities of the Joint Committee on Moulding Sand Research* (American Foundrymen's Association, June 1, 1924). The report contains tests for determining the cohesiveness, permeability, fineness, and dye adsorption properties of moulding sands. Methods for the ultimate analysis of moulding sand and of sampling sand as shipped are also included. The permeability of sand is ascertained by measuring the rate of flow of air through a standard specimen of sand under a given pressure. The application of the dye adsorption phenomenon to moulding sand is solely for the purpose of ascertaining the nature of the clay substance present. Different sands possess widely different adsorption capacities, and this difference is due exclusively to the quantity of colloidal matter present. The colloids in moulding sands are mostly of an inorganic nature: hydrated aluminium silicate, hydrated iron oxide, hydrated silicic acid, and other hydrated minerals. All of these constituents are of a gelatinous and sticky nature and they impart to the sand the property of bond. Strongly bonded sands commonly possess clay substance that is high in colloid content as measured by the dye adsorption test. The weaker bonded sands generally show a lower

dye adsorption figure corresponding to the smaller quantity of colloids present in the clay substance of those sands.

H. W. Dietert, *Commercial Application of Moulding Sand Testing* (Paper read before the American Foundrymen's Association, October 1924). The author describes the apparatus and methods used for the testing of moulding sands at the plant of the United States Radiator Corporation, Detroit. The A.F.A. permeability test, special compression tests, and moisture determination methods are used. Charts are given showing how losses have been reduced by laboratory control.

R. F. Harrington, W. L. MacComb, and M. A. Hosmer, *A Study of the Effect of Heat on the Clay Content of Moulding Sands as Shown by the Dye Adsorption Test* (Paper read before the American Foundrymen's Association, October 1924).

H. W. Highriter, *The Use of Chemical Reagents in Preparing and Rebonding Moulding Sands* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 591-594). The use of alkalies in the preparation and reclamation of moulding sands is briefly discussed. It is suggested that the bond of weak natural moulding sands might be increased by alkali addition, so as to render the sands suitable for use, and that in rebonding used sands by the addition of clays better results with less clay might be obtained through the deflocculation of the clay with alkali or other reagent.

H. M. Lane, *Reclaiming Foundry Sand* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 656-663). The author describes experiments on the reclamation of sand by dry and wet processes.

F. L. Wolf and A. A. Grubb, *Reclamation of Core Sand* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 594-604). The practicability of reclaiming the sand from defective and used cores depends in a large degree upon the kind of binder used in the original core sand mixture. The various types of binders used in making cores are reviewed. The results of tests on linseed oil bound cores and dextrin-bound cores are described. Sand from linseed oil cores, even those which have not been burned, is not so good for core sand mixture as new sand. Not only is no binding value obtained from the oxidised oil, but a larger quantity of oil must be added than is required by new sand. Cores bound with dextrin gave much better results.

C. W. H. Holmes, *The Technical Side of Oil Sand Cores* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, June 26, 1924, vol. 29, pp. 543-547). The author discusses principles and practice in the use of oil sand cores in the foundry.

**Centrifugal Casting.**—C. Pardun, *The Scientific Principles of Centrifugal Casting* (Stahl und Eisen, July 31, August 28, October 2, 1924, vol. 44, pp. 905-911, 1044-1048, 1200-1208). The first attempts at centrifugal casting date from 1809, when Eckhardt took out a patent



in England for the centrifugal casting of metals. His invention, though it covered all essential points for the carrying out of the process, was never brought into practical use, and it was not until 1849 that attention was once more directed to the development of methods of centrifugal casting; from that time onwards many inventors in various countries have occupied themselves with the problem, among them Henry Bessemer, who, in 1857, patented an arrangement for producing rail ingots and blooms in vertically spinning moulds. None of these methods met with any great measure of success until Whitley, in 1880, brought out an improved device for feeding the liquid metal into a spinning mould for pipes; together with S. Fox he introduced the tipping trough, which was inserted into the hollow horizontal mould, filled with exactly the quantity of metal necessary for a single pipe, and this was tipped into the mould evenly throughout its length, after it had begun to rotate, so that the metal did not have to flow longitudinally, but only to take up the spinning motion. The de Lavaud system was first based on this principle, but afterwards an important improvement was made by O. Briede, who, instead of using a horizontal tipping trough, inclined the mould at a small angle and inserted a sloping trough, which was gradually withdrawn as the metal flowed down into the mould. The stream of metal was thus caught up and given a spiral movement directly it touched the spinning mould, and no flow of metal took place in any direction within the mould, the centrifugal motion performing no other function than the even distribution of the metal. De Lavaud adopted this modification of Briede, and that system is the one now in use in many countries for producing pipes by the centrifugal method of casting. The casting of steel centrifugally involves greater difficulties, but a successful process has been developed by Cammen, who pours the liquid steel into a mould previously heated to a high temperature, so that the steel shall remain liquid long enough to spread through the length of the mould.

C. Pardun, *The Scientific Principles of Centrifugal Casting* (Foundry Trade Journal, October 2, 1924, vol. 30, pp. 295-296). A lengthy abstract in English of the above article.

E. J. Fox and P. H. Wilson, *Modern Methods of Pipe Manufacture by the Centrifugal Process* (Iron and Coal Trades Review, August 29, 1924, vol. 109, pp. 344-346). A detailed description, with illustrations, is given of the methods of producing iron pipes by the De Lavaud centrifugal process as carried out at the Stanton Ironworks. The pipe is formed in a cylindrical steel mould, which is revolved on its own axis by means of an impulse water turbine inside a water-cooled iron casing. The casing with its revolving mould is caused to traverse backwards and forwards on its bed-plate by a hydraulic cylinder installed beneath the casing. At one end of the mould a Pelton wheel is fixed, and at the other end are gland rings, somewhat similar to the collar thrust bearings employed in marine work. The only core used is that which



is necessary to shape the inside of the socket. The moulds are poured by means of a cantilever trough, which is projected down the centre of the mould towards the socket end. The Pelton wheel propelling the mould is started and, when the mould has acquired a proper speed, iron is poured from a ladle into the cantilever trough. When the socket is filled the casing is allowed to traverse away from the ladle at a speed which ensures the molten metal lining the inside of the mould evenly throughout its entire length. The molten metal in contact with the water-cooled mould solidifies in a few seconds and, contracting slightly, allows the pipe to be withdrawn. Annealing is necessary to restore the homogeneity of the pipe. The actual making of a pipe takes, on an average, about fourteen seconds, the complete operation from beginning to end occupying seventy-five seconds. The average analysis of the iron used is as follows: Silicon, 2.6 to 2.9; graphitic carbon, 2.7 to 3.0; combined carbon, 0.20 to 0.40; sulphur, 0.050 to 0.068; phosphorus, 1.10; and manganese, 0.38 per cent. The results of tests of pipes made by this process are included. The centrifugally cast metal has a tensile strength 70 per cent. higher than that of cast iron.

R. Moldenke, *Manufacture of Cast Iron Pipe in the South* (Paper read before the American Institute of Mining and Metallurgical Engineers, October 1924). The author discusses some economic conditions in the cast iron pipe industry of the United States. An outline is given of the de Lavaud centrifugal pipe-casting process, and a more recent development of centrifugal casting, in which sand-lined moulds are used. In this process no annealing of the pipe is necessary, as in the de Lavaud process, where the use of steel moulds has a chilling effect on the pipe, which is overcome by a short anneal at high temperature.

*Centrifugal Pipe by a New Process* (Iron Age, June 5, 1924, vol. 113, pp. 1661). Brief particulars are given of a centrifugal process for the production of cast iron pipe. The metal is poured into a rapidly revolving sand-lined flask, against which the metal is cast without any chilling action. Pipes may be cast in any thickness. A refractory lining is applied to the sand-mould before casting to prevent the burning of the sand to the iron, and to avoid scabbing. The sand in the flask is held in place by the centrifugal action. The refractory lining is of such a character that during the casting operation it becomes incorporated by a fusing action with the outer shell of the casting, thus forming a protective coating to the pipe. Pipes made by this process have been tested at 2400 lbs. per square inch.

C. Irresberger, *Present Position of Centrifugal Casting* (Giesserei Zeitung, September 15, 1924, vol. 21, pp. 397-402). Practice in the centrifugal casting of piston rings and pipes is described, with particular reference to the de Lavaud process.

**Malleable Castings.**—T. Levoz, *A European View of the Malleable Question* (Foundry Trade Journal, August 28, 1924, vol. 30, pp. 175-177).

Attention is drawn to the part played by iron oxide in the melting of iron for the production of malleable castings. Ferrous oxide absorbs heat calories in order to be reduced in presence of the carbon, while ferric oxides release them. For this reason it is preferable for the unreduced oxides in the metal to be in the ferric state. If foundrymen had at their disposal a cupola obviating oxidation of the iron, it is evident that such an apparatus would be the ideal method of producing iron for malleable castings, subject to the condition, however, that it should effect fusion at the highest possible temperature. In the author's opinion, the only method of competing successfully with cast steel in Europe is to produce malleable iron on the same system as cast steel. Since 1905 malleable iron has been produced in Germany by melting hæmatite pig in a cupola, afterwards transferring it to a converter in order to desiliconise it. This method was introduced into France with some success. The ordinary bottom-blown Bessemer converter is not suitable for this class of work, as it produces ferrous oxides whilst it is desiliconising the metal. In 1915 the author introduced a triplex process in which the following apparatus is used: A cupola with combustion zone distinctly separated from the zone of fusion in which only reducing gases circulate, a side-blown converter, and an electric furnace.

P. Oberhoffer and E. Zingg, *Formation of Scale in the Malleablising Process* (Stahl und Eisen, October 2, 1924, vol. 44, pp. 1197-1200). Practical observations during the manufacture of malleable castings have confirmed the very important part played by the gas phase, and also that the tendencies towards equilibrium corresponding to the combined diagram of Boudouard and Schenck do exist. It has also been shown by experiments with synthetic mixtures, in which the essential factors were varied within wide limits, that, besides the annealing temperature, the relation of the iron-oxygen combinations in the annealing agent determines the existence of a suitable gas phase, and thus ensures that the annealing proceeds free of irregularity. The tendency for skin and scale to form increases directly as the quartz content in the ore is increased, and also as the silicon in the article to be annealed is increased. Sulphur favours the formation of a defective surface, but manganese appears to counteract this effect of sulphur. The disturbing influence of these impurities diminishes as the gas phase approaches equilibrium conditions, which occurs when the ratio of  $\text{FeO}$  to  $\text{Fe}_2\text{O}_3$  in the annealing medium is approximately 1 to 9.

H. A. Schwartz, *Oxidation Losses during Air Furnace Melting of White Cast Iron* (Paper read before the American Foundrymen's Association, October 1924). The paper is primarily a study of the composition of air-furnace slags obtained under varying degrees of oxidation. The bearing of these compositions on various hypotheses regarding the mechanism of slag formation is pointed out, although no definite conclusions have been drawn regarding the physical chemistry of the process.

*Iron Supply Governs Location* (Foundry, May 15, 1924, vol. 52, pp. 389-394). An illustrated description is given of the lay-out and equipment of the plant of the Cadillac Malleable Iron Co., Michigan, for the production of malleable castings. Charcoal pig is used, which is supplied from an adjoining blast-furnace plant. Charcoal pig is thought to give a metal with less shrinkage, which is more homogeneous than when coke iron forms the basis of the mixture. The finished iron has the following compositions: Silicon, 0.75 to 0.90; sulphur, 0.04 to 0.05; phosphorus, 0.19 to 0.20; manganese, 0.20 to 0.25; total carbon, 2.40 to 2.60 per cent. The methods of moulding, casting, and annealing are described in detail.

E. C. Boehringer, *Malleable Plant placed in Service* (Foundry, July 1, 1924, vol. 52, pp. 521-526, 533; Iron Trade Review, July 3, 1924, vol. 75, pp. 29-33). An illustrated description of the general lay-out and equipment of the new foundry of the Belle City Malleable Iron Co., Racine, Wisconsin, for the production of malleable castings. The furnaces are fired with pulverised coal, and fitted with waste-heat boilers. The slag from the furnaces is discharged into water, and the iron in the slag is recovered by a magnet. A large continuous annealing oven is in operation.

G. L. Lacher, *Reconstructing Plant under Production* (Iron Age, July 3, 1924, vol. 114, pp. 5-9). The above plant is also described.

B. R. Mayne and C. Joseph, *Use of Oil in Malleable Furnace* (Foundry, June 15, 1924, vol. 52, pp. 472-475). An illustrated description of the methods of using oil fuel in malleable iron furnaces at an American foundry.

**Cleaning of Castings.**—W. M. Weigel, *Sand-Blast Sand* (U.S. Bureau of Mines, Serial 2615, 1924). A study has been made of the grades, shape of grains, sizes, uses, and method of mining and preparation of sands for sand-blasting. It was found that great variation exists in the different grades as marketed, and that closer sizing and more uniformity in practice is desirable.

*Cleaning Steel Castings Economically* (Foundry, September 1, 1924, vol. 52, pp. 688-690). An illustrated account is given of the methods of cleaning castings practised in an American foundry.

**Foundry Equipment.**—*The International Foundry Trades' Exhibition, Birmingham* (Foundry Trade Journal, June 26, 1924, vol. 29, pp. 537-542). An illustrated description of various foundry equipment exhibited at this Exhibition. The section and plan of the Schurmann cupola is included.

*A New London Foundry* (Foundry Trade Journal, July 31, 1924, vol. 30, pp. 92-97). An illustrated description of the lay-out and equipment of the new foundry of Harland and Wolff, Ltd., at North Woolwich. The melting plant in the iron foundry consists of two 7-ton cupolas, a 1-ton emergency cupola, and a 7-cwt. reverberatory

furnace. The reverberatory furnace serves as a reservoir in case of urgent repair work. The waste heat from this furnace is utilised in the core stove.

*The Foundries of Messrs. Glenfield and Kennedy* (Foundry Trade Journal, July 24, 1924, vol. 30, pp. 68-70). The general equipment of these foundries at Kilmarnock is described and illustrated.

*The Foundry of the Sunbeam Motor Car Company* (Foundry Trade Journal, June 5, 1924, vol. 29, pp. 455-459). The general outlay and equipment of this foundry are described and illustrated. The grey iron melting is carried out in two cupolas. The foundry is well equipped with moulding machines.

*The Manufacture of Light Castings, Pipes, and Fittings in India* (Foundry Trade Journal, July 3, 1924, vol. 30, pp. 13-15). An illustrated description is given of the plant of the Eastern Light Castings Co., Ltd., Kulti, Bengal, for the production of pipes and light repetition castings.

F. L. Prentiss, *Jobbing Foundry of Ford Motor Co.* (Iron Age, May 22, 1924, vol. 113, pp. 1485-1489). The equipment of the new jobbing foundry of the Ford Motor Co., Detroit, is described and illustrated. The foundry has iron, steel, and non-ferrous departments, and is equipped with three cupolas and three electric furnaces. Direct metal is also supplied from an adjacent blast-furnace.

E. C. Boehringer, *Pours Iron on Second Floor* (Foundry, June 15, 1924, vol. 52, pp. 455-459). An illustrated description is given of the equipment of an American foundry for the production of malleable castings. The iron is melted and poured, and all moulding is done on an upper floor of the foundry.

*Car Wheel Foundry with Parallel Motions* (Iron Age, July 10, 1924, vol. 114, pp. 67-70). The foundry plant of the National Car Wheel Co., Rochester, New York, is described and illustrated. In this plant a moulding unit for the manufacture of chilled iron car wheels, with a capacity of 400 wheels in eight hours, has recently been put into operation. Conspicuous features of the moulding unit include an elevated shake-out grate and gravity conveyors for conveying the cope and drag flasks back to the moulding end of the unit. Straight line parallel conveyors are used, so that turntables and transfers are avoided.

W. J. Corbett, *Cost Finding in a Foundry* (Paper read before the American Foundrymen's Association, October 1924).

H. B. May, *Departmental Costs in the Foundry* (Paper read before the American Foundrymen's Association, October 1924).



# PRODUCTION OF STEEL.

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### I.—PROCESSES OF STEEL PRODUCTION.

**Bessemer and Open-Hearth Processes.**—R. von Seth, *Acid Bessemer Practice in Sweden* (Iron Age, September 11, 1924, vol. 114, pp. 637–638). An English abstract of a paper published in *Jernkontorets Annaler*, 1924, No. 1, giving the results of an investigation of the acid Bessemer practice at various plants in Sweden.

E. Loisy and A. Portevin, *The Metallurgical Work of A. Pourcel* (*Revue de Métallurgie*, April 1924, vol. 21, pp. 197–222). Under the above heading a number of valuable notes have been compiled relating to the metallurgy of iron and steel, based on the researches and investigations made from time to time by A. Pourcel, and a bibliography of his papers is included. The investigations relate to the function of manganese in the acid Bessemer process; linings for metallurgical furnaces; the manufacture of ferro-manganese and silico-spiegel in the blast-furnace; the production of sound steel castings and the influence thereon of silicon and aluminium; dephosphorisation in the open-hearth and the influence of phosphorus; segregation in steel ingots, and a number of miscellaneous questions, such as the influence of nitrogen in steel, and the use of the dry air-blast. Each of the sections is accompanied by details of the work carried out by Pourcel from time to time.

L. Cournot, *The Manufacture of Steel in the Converter; the Discovery of the Process, and its Introduction into France* (*Revue de Métallurgie*, November 1923, vol. 20, pp. 695–711). After a brief account of Bessemer's early experiments, and a list of his patents, the rival claims of Galy-Cazalat are discussed. Galy-Cazalat was born on July 9, 1796, and was Professor of Mathematics and Physics at Perpignan, Nancy, and later at Versailles. His process, which was ultimately applied to the manufacture of steel in a converter, was not originally intended for this purpose, and the earliest patent, the date of which was September 12, 1851, was for producing an illuminating gas by passing the vapour of acidulated water through molten zinc.



The process was not successful, and was amended by several subsequent patents in 1852, 1854, 1855, and 1858, but in none of these patents was there any attempt to refine pig iron by means of a current of air; even in those in which a pig iron refining process is described, the means adopted being a stream of water vapour. It was not until Bessemer's discovery had been perfected that claims were raised in respect of Galy-Cazalat, and it was not until much later patents had been taken out by the latter that any reference was made to refining the molten bath of pig iron by means of an air current, and even then the reference is an indirect one to which little importance can be attached. An account is given of the investigation carried out by Jordan and published in 1869, in which the Galy-Cazalat claims are practically dismissed and those of Bessemer fully recognised. An account is given of the introduction of the Bessemer process in France by James Jackson & Sons, at their works at St. Seurin, near Bordeaux, in 1858. The Jackson interests were subsequently absorbed by the Imphy Company, who were satisfactorily carrying out the process in 1864, under the guidance of Frémy.

G. A. V. Russell, *Some Recent Developments in Open-Hearth Steel Practice* (Paper read before the Yorkshire Association of the Institution of Civil Engineers: Iron and Coal Trades Review, August 1, 1924, vol. 109, pp. 197-198). The subject is discussed under the following headings: Limitation of furnace charges, furnace hearths, coke-oven gas, mixed gases, thermal efficiency, furnace regenerators, furnace construction, and handling of melting-shop materials.

A. Jung, *The Absorption of Sulphur from the Fuel Gas in the Open-Hearth Furnace* (Stahl und Eisen, July 31, 1924, vol. 44, pp. 911-914). At the Peine Steelworks it became necessary in 1923 to use brown-coal for the production of gas for the steel furnaces. One class of briquettes from a certain mine contained up to 4 per cent. sulphur, but later another class of briquette became available with sulphur from 2.8 to 0.6 per cent. Opportunity was thus afforded of investigating the effect of gas containing different proportions of sulphur on the product. The sulphur in the ingot was higher, the higher the sulphur in the gas, but not in the same proportion, as the sulphur taken up from the gas was divided between the bath and the slag. If the sulphur in the gas exceeds 3 grammes per cubic metre, fluorspar must be added if the sulphur in the bath is to be kept below 0.06 per cent.

H. D. Hibbard, *Partly Killed Simple Steels* (Iron Age, September 4, 11, 1924, vol. 114, pp. 565, 599-600, 631-633). Partly killed steel may be defined as that which contains harmful gas holes. Killed steel contains no gas holes whatever, and full effervescing steel contains only such as are practically harmless. The steels considered in the paper are mostly those made in the basic open-hearth furnace, and top cast in ordinary ingots of 1 to 3 tons weight. The completeness with which steel, not effervescing, is killed depends: (1) On the treatment it receives in the furnace during and after melting; (2) on the

casting temperature; and (3) on the additions, made at the end, of reagents which prevent the separation of gases during solidification. Killed and settling steel should always be cast in moulds with the larger end up to minimise pipe. Partly killed steels which do not settle, and effervescing steels may be cast into moulds, small end up, as there will be little or no pipe because of the gas holes formed in them. In this article partly killed steels are divided into soft steels having less than 0.40 per cent. carbon, medium steels with from 0.40 to 0.70 per cent., and hard steels containing over 0.70 per cent. These steels may either rise or stand, or even settle somewhat in the mould, according as they are more or less nearly killed. The characteristics of rising, standing, and settling steels are discussed.

Vivanti, *The Use of Titanium in the Manufacture of Steel* (Metalurgia Italiana, January 1924, vol. 16, pp. 5-12). Titanium is most usually employed in the form of ferro-carbon-titanium, manufactured in the electric furnace and containing on an average titanium 15.79, carbon 7.46, silicon 1.41, and aluminium 0.8 per cent., with very small percentages of manganese, sulphur, and phosphorus. Ferro-titanium, carbon-free, is made by the thermit process, and contains 25 per cent. titanium and about 5 per cent. aluminium. The excellent deoxidising effect of titanium is due to the fact that it forms very fluid, easily fusible products of deoxidation, which immediately rise to the surface and unite with the slag. The products of deoxidation formed by the use of aluminium are not very fluid at furnace temperature, as the aluminium combining with silica forms a very viscous slag. Segregation is lessened by the use of titanium, probably for the reason that gas bubbles do not remain entangled in the mass of solidifying steel, but rise quickly, entraining with them the impurities which collect at the top before they solidify. Some comparative tests of rails and plates of steel treated with titanium and of other rails and plates not so treated, are given, but in the latter case the deoxidising agent used is not stated. The titanium-treated products gave the better results of the two sets, but in the absence of further particulars no particular conclusion can be drawn.

H. Obermeyer and A. L. Greene, *Böhler Steel* (Blast-Furnace and Steel Plant, June 1924, vol. 12, pp. 281-284). A short account is given of the products of the old-established steelworks of Böhler Brothers, whose chief factory is at Kapfenberg, in Austria. The conditions under which the firm continues to carry on its extensive trade are described.

J. B. Rhodes, *The Manufacture of Steel for Ordnance Purposes* (Paper read before the American Iron and Steel Institute, May 1924). The author discusses some fundamental reactions and conditions in steel-making processes, the paper being largely devoted to the subject of slag conditions.

P. M. Macnair, *Slag Metal Reactions* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 267-294).

A. Pavloff, *The Changes Undergone in the Dimensions and Design of Open-Hearth Furnaces* (Revue de Métallurgie, September 1923, vol. 20, pp. 607-612). After a short survey of the design and construction of open-hearth furnaces during what may be termed the first period of their use (1865 to 1880), followed by a similar review of the furnaces employed in the transition period of 1880 to 1895, the modern types of furnaces now in use are described, more particularly from the point of view of their departures from the original designs. A table is given showing the dimensions of modern open-hearth furnaces having a capacity of 50 tons or more drawn from French, German, British, American, and Russian sources, and reference is made to an earlier table published by the author, giving the dimensions of a number of earlier furnaces as used in the countries enumerated. The changes in design which have occurred since the open-hearth furnace was invented involve principally the roof, the ports, and the regenerators, and the subject is considered from each of these points of view, the changes in regenerators, due to changes in the type of fuel used (including pulverised coal), being more particularly indicated. A brief mention is made of waste-heat boilers for open-hearth furnaces as used in American practice.

W. E. Groume-Grjmailo, *A Critical Study of Industrial Furnaces in the Light of the Author's Theory, based upon the Laws of Hydraulics* (Revue de Métallurgie, October 1923, vol. 20, pp. 687-693). As illustrations of the necessity of designing industrial furnaces, with due regard to the laws of hydraulic flow, the Schurmann cupola, a waste-heat steam boiler at an open-hearth furnace plant, an underfeed boiler with an Usco superheater, and a Siemens mill furnace are taken, and adversely criticised. The ideal state of affairs is represented diagrammatically by a mill heating furnace having four ports at each end, a correct roof, and conforming to the essentials for securing proper regard for hydraulic flow conditions in heating fluids.

**Electric Steel Furnace Practice.**—F. Sommer, *Progress in the Production of Electric Steel* (Stahl und Eisen, May 1, 8, 15, 1924, vol. 44, pp. 490-496, 526-530, 553-558). A comparison of the efficiencies of the induction furnace and arc furnace shows that the energy consumption of an induction furnace per ton of steel is considerably higher than in an arc furnace, chiefly owing to conversion and transformer losses, but the difference is almost equalised on account of the much greater radiation losses and losses in transmission of the arc furnace than those of the induction furnace. It is proposed that inquiry should be set on foot for the purpose of obtaining data as to kilowatt consumption and other factors, in order to establish an electric energy balance for different types of furnaces. Statistics of existing electric furnaces and of electric steel production are given. These show that the United States and Italy are now in advance of all other countries in output of electric steel, principally in the form of castings. The metallurgical processes in the electric furnace are also fully described.

F. T. Sisco, *Fluorine in the Deoxidising Slag, and its Influence on Refractories in Basic Electric Furnace Practice* (Paper read before the American Electrochemical Society, October 1924). The deoxidising slag in basic electric furnace practice is made up of lime, coke, and fluorspar in the ratio of approximately 6 : 1 : 1. At the high temperature present in the deoxidation period, the fluorspar is acted upon by oxygen, oxides, carbon, or by heat alone. The fluorine set free reacts with silica in the roof and upper walls of the furnace to form silicon tetrafluoride. Part of this constituent escapes, part enters the slag, where it reacts with lime to form calcium silico-fluoride. The activity of fluorine results in an increase in the silica content of the slag at the expense of the roof and side walls. This enrichment amounts to 100 lbs. of silica or more each heat, and results in one-quarter to one-half of the total weight of the roof and upper side walls being worn away during the life of the refractories. Fluidity of the deoxidising slag is obtained, when fluorspar is used, by the formation of calcium silicates and calcium silico-fluorides, and by the presence of calcium fluoride. When silica sand is substituted, wholly or in part, for fluorspar, the fluidity is obtained mostly by the formation of calcium silicate. With fluorspar it is possible to maintain a much higher degree of basicity for the same fluidity than is possible with silica sand. Fluorspar is also a direct aid in desulphurising, while silica sand is not. Another important advantage is that it is much easier to maintain strongly reducing conditions, by an excess of calcium carbide, if fluorspar is used. The corrosion of the refractories, while considerable, is not so great as to warrant discontinuing the use of fluorspar if properly controlled.

K. Kerpely, *Considerations in the Construction of Arc Furnaces* (Giesserei Zeitung, June 15, July 1, 15, August 1, 1924, vol. 21, pp. 242-247, 277-282, 320-325). The construction and equipment of arc furnaces for use in the steel foundry are illustrated and described, and the relative efficiencies of the Heroult and Fiat furnaces are compared.

**Steelworks Equipment.**—G. L. Lacher, *Wisconsin Steelworks adds Open-Hearth* (Iron Age, May 15, 1924, vol. 113, pp. 1421-1425). An illustrated description is given of the new open-hearth plant recently completed by the Wisconsin Steelworks, South Chicago. The new plant comprises five 100-ton basic furnaces. Plans are provided for the construction of six additional furnaces. For the furnaces now in operation the use of water for cooling has been reduced to a minimum. Another feature of the furnace is the absence of hydraulic equipment for operating the doors and reversing valves, electric motors being used for this purpose. Oil atomised by steam, together with some coke-oven gas is burned directly in the furnaces. The usual separate gas and air chambers have been provided at the ends of the furnaces, but the gas chambers are now used for air also and will be utilised for gas only in case it is decided later to use producer-gas as a fuel.

*Electric Steel in Brazil* (Iron Age, June 26, 1924, vol. 113, pp. 1863-1864). An illustrated account is given of the first electric steel plant



erected in Brazil. The Company operating the works is the Companhia Electro Metallurgica Brasileira, Ribeirao, Preto. The plant is completely operated by electricity, and pig iron, steel, and rolled products are produced. Iron ore is obtained from Morro do Ferro. Two large Electrometal smelting furnaces fitted with Soderberg electrodes are in operation for supplying iron to the steel plant, which consists of two 6-ton Bessemer converters, and one 6-ton Ludlum electric steel furnace. The rolling-mill plant consists of a three-high 16-inch roughing mill and a three-high 10-inch finishing mill.

F. A. J. Fitzgerald, *Electricity in Steel-Making* (Paper read before the World Power Conference, London, July 1924). The author describes the development of the hydro-electric system of the Niagara Falls Power Co. and of the industries to which power from this source has been supplied. The manufacture of electric steel for castings requires much higher temperatures than those required for melting non-ferrous alloys, such as brass or bronze; but it is shown that electric heating competes successfully with fuel, even in places where the cost of electric energy is relatively high.

## II.—CASTING AND TREATMENT OF INGOTS.

**Heterogeneity of Steel Ingots.**—K. G. Troubine, *A Hypothesis Relative to the Origin of Surface Blowholes in Steel Ingots* (Revue de Métallurgie, May 1924, vol. 21, pp. 288–294). While explanations are forthcoming as to the formation of pipes in steel ingots those relating to the formation of surface blowholes are not as yet satisfactory. Such blowholes arise in a wild steel when the occluded gases escape during solidification. The extent to which they do so is related to the percentage of silicon in the steel, or, in other words, to the methods of deoxidation employed during the manufacture. Such blowholes are not, however, peculiar to wild steel, but are also found on the exterior of dead melted steel. They are even larger in proportion as the size of the ingot increases. It is probable, however, that the blowholes observed in the case of wild steel and those which occur with steel which has been quiet in the ladle arise from different causes. The latter may often be due to the air which is introduced in the stream of molten metal, the surface tension of which is such as to offer considerable affinity for air, which is subsequently entangled in the mass of the steel, and escapes on the surface. When ingots gassed in this way are subjected to compression, as in the Whitworth process, the exterior blowholes are suppressed, for the zone which would otherwise contain them becomes redissolved while the mould is being filled. This dissolution of the exterior crust is accompanied with a boiling action, which takes place in contact with the walls of the ingot mould. The material of which the latter is made appears to have considerable influence on the depth at which exterior blowholes can be



found, particularly when the steel is wild, and, generally speaking, the effect of the mould on the rate of cooling likewise exerts its influence. It is possible that, on shrinkage, part of the gases which have been imprisoned in the pipe find their way to the surface.

J. Pot, *Method for Ascertaining if a Mass of Steel is Identical Throughout* (Revue de Métallurgie, November 1923, vol. 20, p. 770; abstracted from the Journal des Connaissances utiles, August 1833, p. 224). A brief note of considerable historical interest, stating that as the value of steel depends upon its homogeneity, a simple method can be adopted to ascertain the degree of homogeneity it possesses by polishing one or more surfaces, and exposing them to the action of dilute nitric acid, or aqua fortis. By the action of the acid, stains are made to appear which are due to the presence of carbon intermingled with iron carbide. If the stains be regularly distributed the steel is homogeneous. If, however, they are irregularly distributed, the test reveals a lack of homogeneity which renders it unsuitable for certain purposes. It is further recorded that, whilst this method of assay has been attributed to English sources, its origin is really French, as it was first employed by a cutler of the name of Pernet, who had, years previously, established a highly esteemed business in France.

W. Oertel and L. A. Richter, *The Influence of Deoxidation on the Hot-Working and Properties of a Nickel-Chromium Structural Steel* (Report No. 3 of the Laboratory of the Glockenstahlwerke, Remscheid, 1924, 7 pp.). The authors report the results of an investigation into the causes of rolling cracks and other defects in nickel-chrome steel. The influence of teeming temperature, teeming speed, heat conductivity of the mould, rolling temperature, and length of soaking time were studied. The quality of the steel really depends on the careful deoxidation of the bath and the elimination of gases. The proper use of ferro-manganese as the best agent for deoxidising is discussed. The influence of all the factors was determined by means of the usual tensile and impact tests.

**Centrifugal Casting of Sheet Bars.**—L. Cammen, *Sheet Bars Cast Centrifugally* (Iron Age, June 26, 1924, vol. 113, pp. 1857–1858). In the new Cammen centrifugal casting process, bars or small ingots are produced by running the finished charge of the steel furnace direct into bottle-neck moulds rotating at a high speed. The operation is accomplished without the formation of cold shot which usually accompanies attempts to cast centrifugally in divided moulds. In the bottle-neck mould the metal is fed against the smooth part of the mould, and is propelled along the axis of the mould so that by the time it reaches the divided partitions, the metal is already whirling at the same speed as the mould. There is, therefore, no shock, and the metal flows gently past the partitions filling the intervening spaces. The structure of bars produced by this method is shown by photomicrographs, together with the results of physical tests.

## FORGING AND ROLLING-MILL PRACTICE.

**Forging Practice.**—H. Southern, *The Furnace Equipment of Mills and Forges* (Proceedings of the Cleveland Institution of Engineers, Session 1923-24, pp. 241-272). The subject is discussed under the following headings: Fuel consumption in steelworks; the influence of plant lay-out upon the consumption of fuel; fuels and furnace design; the furnace equipment of rolling-mills and forges; and the consumption of fuel in furnaces as affected by irregularity of operation. Several charts are given, one representing a heat balance of an uneconomical steel plant indicating the distribution of heat in an average American plant of twenty-five years ago. Another indicates the heat balance of an average present-day American steel plant. From this chart it is noted that  $1\frac{1}{2}$  lb. of coal are consumed in the production of 1 lb. of rolled steel, 0.45 lb. being used in the open-hearth and mill furnaces. This is equivalent to a consumption of 9 cwt. of coal per ton of finished steel, the open-hearth furnaces taking 5.19 cwt., the soaking pits 0.86 cwt., and the reheating furnaces 2.95 cwt. It has been assumed in each case that one-half of the product is rolled into 1-inch square bars and one-half into 8-inch joists, and that 1.26 ton of ingots are required to produce 1 ton of finished rolled steel. The average present day American plant is producing 1 ton of finished steel from iron ore, with a consumption of coal 15 cwt. per ton less than was the case twenty-five years ago. Comparing English practice it is noted that one firm in the Midlands is producing finished rolled billets from scrap with a coal consumption of 8.97 cwt. per ton, the open-hearth furnaces taking 6.6 cwt., and the soaking pits 2.37 cwt., whilst another plant in South Wales is producing finished sheet bar from scrap with a consumption of 8.24 cwt. per ton. In the latter plant the open-hearth furnaces consume 5.64 cwt. of coal per ton of steel, and the ingot heating furnaces 2.6 cwt. Various types of heating furnaces are illustrated. The continuous furnace is the most satisfactory equipment to instal in connection with any mill which produces material from blooms or billets of uniform size.

H. Cassin, *The Rational Utilisation of Gaseous Products by the Surface Combustion Process* (Revue Universelle des Mines, June 15, 1924, vol. 2, pp. 340-345). Deals briefly with surface combustion, using coke-oven or natural gas, and contains references to its employment in metallurgical furnaces, and more particularly in mill reheating furnaces in America and in France.

A. Weyel, *Trials with Coal-Dust Fired Soaking Pits* (Stahl und Eisen, August 14, 1924, vol. 44, pp. 977-979). Results of trials in firing ingot soaking pits with powdered coal are reported. Using brown-coal dust the consumption was 14 per cent. by weight of the charge, and with hard coal 9.6 per cent. of the charge. For grinding the coal the power consumption amounted to 9.6 kilowatt-hours, and for blowing the dust and air for combustion into the furnace another 11.2 kilowatt-hours were consumed.

J. R. Adams, *Hardened and Ground Rolls* (Paper read before the American Iron and Steel Institute, May 1924). For the purposes of the paper hardened and ground rolls are considered as forged steel rolls, hardened and drawn, the drawing being insufficient to make the rolling surface machinable, so that it must be ground to be finished. Hardened and ground rolls differ from chilled rolls in that they have greater hardness, more homogeneous surface, greater strength and longer life. In the manufacture of these rolls the use of alloy steels meet the more exacting requirements. A number of different compositions have been used by various makers, but roll manufacturers at the present time have adopted compositions that more or less fall within the following percentages: Carbon, 0.70 to 1.25; manganese, 0.20 to 0.40; silicon, 0.15 to 0.30; chromium, 1.50 to 2.50 per cent. Hardened and ground rolls are usually made from acid open-hearth, electric, or crucible steel. The ingots are usually cast in such a size that the reduction in forging is not less than 1:3. After annealing, the forgings are preliminarily machined, sufficient material being left above the finished size to allow for further heat treatment before hardening. Hardened and ground rolls preserve their state of high finish for a considerably longer period than chilled iron rolls.

O. W. Ellis, *An Investigation into the Effect of Constitution on the Malleability of Steel at High Temperatures* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 47-81). The fact that it is possible to determine roughly the positions of certain of the critical points by examination of the malleability temperature curve for a given steel, proves that the constitution of steel has a marked effect upon its malleability.

*Drawing Double-Walled Steel Shells* (Machinery, June 12, 1924, vol. 24, pp. 333-335). The methods and dies employed in the drawing and forming of steel shells are described and illustrated. These shells are used in connection with an auxiliary mechanism of alternating current motors and are generally known as spring barrel tubes.

L. N. Brown, *Selecting Material for Drawn Parts* (Blast-Furnace and Steel Plant, May 1924, vol. 12, pp. 239-242: Paper read before American Institute of Mining and Metallurgical Engineers). A method is described for testing sheets and strips to show their suitability for forming and drawing operations.

*Pressed Metal Production* (Machinery, June 12, July 3, 1924, vol. 24, pp. 328-331, 417-421). An illustrated description of the methods

employed at the works of Fisher & Ludlow, Ltd., of Birmingham, for the production of pressed-steel parts.

Virmaud, *Hydraulic Presses* (Arts et Métiers, November 1923, pp. 801-808). A classification of the various types of hydraulic presses in use with notes of the water consumption and of the power developed, and its utilisation in steelworks. The largest presses used up to the present exert a pressure of 14,000 tons. Their use for the compression of liquid steel in ingot moulds is briefly referred to.

L. Aitchison, *Drop-Forge Practice—Trimming the Flash* (Lecture before the British Association of Drop-Forgers and Stampers, November 21, 1923: Forging, Stamping, Heat-Treating, April 1924, vol. 10, pp. 148-152, 172). The article is a continuation of the author's lecture discussing the factors that should be taken into consideration in trimming the flash from drop-forgings and the proper design of tools for the purpose. On the sides of a forging the flash is forced out between the dies in a direction at right angles to the direction of the grain, and at the ends it is forced out parallel to the direction of the grain. The trimming operation should accordingly be adapted to cut through the fibres which have spread in these different directions.

C. C. Hermann, *Machine Forging Dies* (Machinery, May 15, July 10, September 11, 1924, vol. 24, pp. 205-207, 453-455, 740-742). A series of articles on the design and use of forging dies.

W. Anslow, *Drop-Forging Dies—Lay-out and Design* (Journal of the Association of Drop-Forgers and Stampers; Forging, Stamping, Heat-Treating, July 1924, vol. 10, pp. 250-254). The article deals generally with the design of dies, comparing British and American practice.

*The Modern Forging and Stamping of Steel* (Metal Industry, June 20, 27, 1924, vol. 24, pp. 605-606, 627-628, July 4, 1924, vol. 25, pp. 9-11). A survey of forging and stamping practice from a practical point of view.

**Rolling-Mill Equipment and Practice.**—Johnstone-Taylor, *British Rolling-Mill Engine Design* (Iron Age, June 12, 1924, vol. 113, pp. 1717-1719). An illustrated description is given of the 25,000 horsepower reversing engine installed at the Cargo Fleet Ironworks.

*A Large Blooming Mill in France* (Iron and Coal Trades Review, July 25, 1924, vol. 109, p. 164). Illustrated particulars are given of the Sack blooming mill recently erected at the plant of the Société des Acieries de Longwy. The rolls are 46 inches in diameter and 120 inches in length. The mill is driven by an electric motor having a torque of about 1,595,000 foot-lbs., and the Ilgner system of control is employed. The mill is said to be the largest in Europe.

*New Butt Weld Mills at Indiana Harbour* (Iron Age, July 3, 1924, vol. 114, pp. 1-4). An illustrated description of the plant of the Youngstown Sheet and Tube Co., at Indiana Harbour, for the rolling of skelp and the production of butt welded tubes. The skelp is charged



into the welding furnace chamber by a magnetic charging machine. This consists of a roller table having hollow rollers fitted inside with magnets. The magnetic attraction makes up for the lack of weight in the skelp and overcomes the tendency of the skelp to slip off the rollers. At the delivery end of the furnace the welder grasps the pointed end of the heated skelp with a tong, then slips a bell over the tong and places the tong in the end of a draw-bench, where it is automatically gripped by a continuous chain belt which pulls tong and skelp through the bell. The draft through the bell curves the skelp into tubular shape and welds the edges. Each welding furnace has a capacity of 200 tons of pipe per twenty-four hours.

G. L. Lacher, *New Inland Merchant and Billet Mills* (Iron Age, August 7, 1924, vol. 114, pp. 303-307). The merchant and billet mills recently completed at the plant of the Inland Steel Co., Indiana, are described and illustrated. The merchant mill has an estimated capacity of 12,000 to 14,000 tons of finished steel per month. It is a combination of the continuous and staggered duo-type. It is two-high throughout and contains six 18-inch continuous roughing stands and four staggered 14-inch finishing stands. The 24-inch billet and slab mill consists of six continuous two-high stands.

*New Billet and Strip Mills at Bridgeport* (Iron Age, August 28, 1924, vol. 114, pp. 504-505). The lay-out of the proposed new billet and strip mills of the American Tube and Stamping Co., Bridgeport, is described.

G. L. Lacher, *Improved Rail and Track Supply Plant* (Iron Age, August 28, 1924, vol. 114, pp. 495-499). An illustrated account is given of the alterations carried out in the finishing department of the rail mill of the Colorado Fuel and Iron Co., Pueblo, in order to deal with 39-foot rails. The equipment for the production of angle bars and track bolts is also described.

*New Types of Bearings for Rolling-Mills* (Iron Age, August 21, 1924, vol. 114, pp. 442-443). An abstract in English of the article by D. C. Holzweiler, which appeared in *Stahl und Eisen*, April 17, 1924, vol. 44, pp. 361-363.

H. Cramer, *Calculation of Draughts for Rail-Rolling* (*Stahl und Eisen*, August 21, 1924, vol. 44, pp. 1012-1015). Calculations are given to determine the correct position of the neutral axis of passes and diameters of rolls for rail-rolling.

C. W. Gennet, jun., *Late Developments in Steel Rail Practice* (Iron Age, June 12, 1924, vol. 113, pp. 1721-1722). Recent developments in American steel rail practice are discussed. Rails are now being made in 39-foot lengths with milled ends. By the use of these longer rails instead of the prevailing standard 33-foot, the number of joints has been reduced 15 per cent. Notwithstanding that present interest in the rail problem centres chiefly on the mechanical matters, the problem of obtaining sound ingots is still a pressing one. It can be shown that half of the trouble with rails in service occurs in the rails from the



top of the ingots. In the case of the large 14,000-lb. ingots, it is highly probable that the second rail is frequently as bad as the top rail from the smaller 8000-lb. ingot. Certainly the development in steelworks practice in the direction of using larger units, so economically desirable from a mill standpoint, has had an adverse effect on the quality of rails rolled from near the top of the ingots. When the yield of merchantable material is such an important factor it would seem that the use of hot top ingots, inverted moulds, and other devices should be taken advantage of in an effort to obtain not only a higher efficiency of operation, but improvement of quality. Certain railroads are obtaining relief from the pernicious influence of top rail by some method usually made possible by a particular mill condition. Use of the top ingot metal for tie plates is logical and has a very strong interest. The chemical composition of modern rail steel is frequently the subject of discussion, and arguments are advanced favouring the use of higher phosphorus content to offset the high carbon, and, perhaps, the use of more manganese. Trials of some such steel are being suggested, the idea being to produce steel in the open-hearth furnace of more nearly the physical and chemical characteristics of the old time Bessemer rails, which actually gave longer life and were apparently free from some of the defects so often associated with high carbon steels.

H. Hiltehaus, *Automatic Cooling Beds* (Stahl und Eisen, July 3, 1924, vol. 44, pp. 777-784). Cooling beds of various types and fitted with different designs of transporting gear are illustrated and described.

M. Farmer, *Cold-Rolled Strip Steel* (Transactions of the American Society for Steel Treating, June 1924, vol. 5, pp. 590-598). The author deals briefly with the numerous factors involved in the production of cold-rolled strip steel. Casting temperatures, the segregation of elements within the ingots, the rolling of ingots into billets and slabs, and the high-speed rolling of billets, pickling, and the subsequent cold-rolling operations are discussed. A brief review of the various grades of cold-tempered strip is given, and the use of strips for special types of work is also dealt with.

P. Dumartin, *Electric Drive for Rolling-Mills and its Associated Problems* (Revue de Métallurgie, October, November, December 1923, vol. 20, pp. 625-655, 724-753, 796-829). The author begins by discussing the considerations which should govern the question of adapting rolling-mills for electrical driving, and institutes a brief comparison between the principles involved in electrically driven mills and those driven by steam-engines, the relative advantages and disadvantages of each being stated. A section is then devoted to a calculation of the power required, which will differ according to whether the mills are continuous or reversible. Reduced to its simplest factors these calculations depend on the arrangement of the housings, the diameter of the rolls, and the nature of the passes; the weight, section, volume, quality, and temperature of the metal to be rolled; the nature

of the final section aimed at; the hourly production, and such subsidiary considerations as the number of passes required and the reheating operations involved. Each of these factors is described in detail, together with the necessary calculations, and numerous diagrams are given. The next question is the use of fly-wheels in electrically driven rolling-mills, and this is likewise discussed in full, and descriptions are given of rolling-mills thus equipped. The various types of mill motors are enumerated, and their relative merits discussed, after which the whole question of supply is considered in considerable detail. The special requirements of two-high and three-high mills, the nature of the works distributing systems, and the necessity or otherwise for establishing sub-stations are dealt with. The conclusions arrived at are that there is no one set of general rules applicable in all cases, but that every mill requires its own individual treatment, and that while theory may serve very largely to guide in making the arrangements, reliance must chiefly be had on experience, and that such experience can only be obtained from a mill actually at work, and will even then only serve to determine the conditions which should be adopted in a strictly similar mill. The advantages of electricity are its elasticity and the ease with which special modifications may be introduced in design according as practice dictates.

G. Bulle, *Time Recording and Power Consumption Measurements in Rolling Steel* (Stahl und Eisen, August 7, 1924, vol. 44, pp. 937-940). A method is described for recording graphically the time and power consumption at each pass of the material through the rolling-mill.

G. Fox, *Power Consumed in Rolling Steel* (Paper read before the American Iron and Steel Institute, May 23, 1924). The subject is discussed under the following headings: Ratio of demand to connected load; power consumed by main roll drives; power consumption *versus* elongation, and power consumption *versus* rate of rolling. Particulars as to the normal average power consumption of several plants of varied size and type are tabulated. A number of curves are also included in the paper showing the total power consumption as related to elongation in several types of mills.

B. R. Shover, *Power in the Iron and Steel Industry in America* (Paper read before the World Power Conference, July 1924; Iron and Coal Trades Review, July 18, 1924, vol. 109, pp. 101-103). The author estimates that the steel industry of America consumes, for power purposes only, more than 12,400,000 tons of coal per year for the average production. The consumption of electrical energy in rolling-mills is given as 2,500,000,000 kilowatt-hours of which 17 per cent. was purchased from power companies. A marked feature of the electrification of rolling-mills is the almost exclusive adoption of turbo-generators in new installations.

C. Köttingen, *Applications of Electric Power in German Industry* (Paper read before the World Power Conference, London, July 1924). The author describes the applications of electric power in German

industry and enumerates the advantages of electric power transmission for rolling-mills.

W. Geyer, *Electrical Engineering as a Leading Factor in the Development of Modern Steelworks* (Paper read before the World Power Conference, London, July 1924 : Iron and Coal Trades Review, July 25, 1924, vol. 109, pp. 153-154). The improvements made by electrical engineering in iron and steel works are particularly noticeable in centralised power production and in the power distribution system. In combined iron and steel works blast-furnace gas-engines are now principally used as prime movers for the electric generators and air compressors. Gas-engines have not been able to maintain their position except where whole groups of them could be used for centralised power production. The attempts to use blast-furnace gas-engines for driving rolling-mills failed owing to lack of overload capacity and their inability to meet the demands of speed regulation. The application of electric drives has caused a complete change in the general layout and in the working conditions of rolling-mills. The mills are no longer tied to the proximity of boiler batteries and can be arranged so as to produce the finished material in the shortest time. The advantages of steel production in electric furnaces are also briefly dealt with.

E. Poncelet, *Rolling-Mill Administration* (Revue de Métallurgie, May 1924, vol. 21, pp. 255-259). A brief summary is given of various considerations which affect the economy of rolling-mill practice, including the choice of fuel in the mill furnaces, the differential power consumption in mills of different type, the type and control of the labour required, maintenance, and the collection and utilisation of mill waste.

## FURTHER TREATMENT OF IRON AND STEEL.

**Case-Hardening.**—V. E. Hillman, *Gases evolved during Carburisation* (Iron Age, September 11, 1924, vol. 114, pp. 611-614). The author has investigated the gaseous products of a number of carburising compounds. They contained calcium, barium, magnesium, or sodium salts in the form of carbonates. The maximum working temperature used in the investigation was 1550° F. It was found that slow or accelerated heating does not alter the analysis of the gas evolved at the several temperatures adopted. For a given temperature, there is a definite maximum concentration of carbon monoxide. At higher temperatures the activity of the cements investigated is due essentially to carbon monoxide. The evolution of carburising gases practically ceases at 1550° F. This value is nearly consistent with the complete dissociation temperature of calcium carbonate. The maximum percentage of carbon monoxide is found within the range 1400° to 1500° F. The upper value is nearly consistent with the best temperature for cementation. The mechanical properties of the steel, in particular brittleness of the core, are less affected at 1550° F. than at any other carburising temperature. Prolonging the time at 1550° F. does not give rise to appreciable volumes of gas. Herein lies the advantage of luting carburising boxes. Boxes sealed with fireclay prevent the escape of the active gases which are present in the carburising box at 1550° F. If the carburising gases were not entrapped, heating above this temperature and prolonging the time would be futile toward appreciably increasing the depth of case. All the compounds investigated gave rise to a saturated hydrocarbon, namely, methane. Sufficient methane is evolved at 1100° F. to effect some degree of carburisation. Charpy maintains that he obtained true cementation as low as 1050° F. with this gas. The illuminants or unsaturated hydrocarbons were at all times less than 1 per cent.

B. F. Shepherd, *A Few Notes on the Shimer Case-Hardening Process* (Transactions of the American Society for Steel Treating, May 1924, vol. 5, pp. 485-490). This paper includes curves and photomicrographs showing the depth of penetration and structure of steel case-hardened by the Shimer process. In this process the base of the bath is a mixture of sodium and calcium chlorides. This bath is given case-hardening properties by adding small lumps of calcium cyanamide.

J. C. McCullough and O. M. Reiff, *Prevention of Case-Hardening by Copper-Plating* (Industrial and Engineering Chemistry, June 1924, vol. 16, pp. 611-613). Specimens of high-quality steel were copper-plated locally and were then case-hardened in an electrically heated



furnace, the carburising medium employed being a mixture of three parts of wood charcoal and two parts of barium carbonate ground together. The results show that copper-plating is an absolute protection to steel against the penetration of carbon, unless the coating is not continuous, or porous owing to defective disposition of the copper. Slag spots in the steel may also cause perforations. Perforations may be detected by dipping the plated specimen in a solution containing 5 grammes of potassium ferricyanide and 5 grammes of hydrochloric acid with water added to make up 1 litre. Volatilisation of the copper may also take place due to prolonged heating.

T. P. Campbell and H. Fay, *The Case-Hardening of Steel by Boron and Nitrogen* (Industrial and Engineering Chemistry, July 1924, vol. 16, pp. 719-723). An investigation was made with a view to finding what effects could be produced by case-hardening with boron instead of with carbon, and also what effect nitrogen would have on a steel thus treated. Low-carbon steel specimens were heated at various temperatures in finely divided ferro-boron for different lengths of time at temperatures of 800°, 850°, and 900° C. It was found that boron penetrates the steel in much the same manner as carbon under similar conditions, but the boron-hardened steels show a difference in their response to heat-treatment and are never so hard as steels containing an equivalent amount of carbon. Nitrogen is much more readily absorbed by a boron steel than by a carbon steel, this increase in absorptive power being due to the formation of boric nitride at temperatures above that at which iron and nitrogen unite to form a stable nitride. Boron steels thus nitrified show those properties to be expected in a steel of high nitrogen content: extreme brittleness and a marked tendency towards exfoliation, chipping, &c. Analytical data, hardness numbers and photomicrographs are given in support of the authors' conclusions.

**Heat Treatment of Steel.**—Sauvageot and H. Delmas, *Investigations on the Hardening Capacity of Dead Soft Steel at Very High Temperatures* (Revue de Métallurgie, December 1923, vol. 20, pp. 777-795). Dead soft steels containing a maximum of 0.1 per cent. of carbon have, in ordinary circumstances, a very low capacity for hardening, but in the course of certain experiments on the heating of such steel to very high temperatures it was observed that, if the metal was quenched from such temperatures, it became much harder than when quenched at normal temperatures. The experiments were carried out at Creusot, and the apparatus employed is described and illustrated. Dead soft open-hearth steel and an Armco iron were used in the tests. The analysis is shown below:

	Open-Hearth Steel.	Armco Iron.
Carbon . . . . .	0.090	0.064
Silicon . . . . .	0.033	0.044
Sulphur . . . . .	0.022	0.027
Phosphorus . . . . .	0.008	0.029
Manganese . . . . .	0.330	0.065
Copper . . . . .	0.110	nil



In the case of the dead soft steel the ball hardness results, when quenching was carried out at a temperature varying from  $950^{\circ}$  to  $1350^{\circ}$  C., show an insignificant amount of hardening, but above  $1400^{\circ}$ , and more particularly in the vicinity of  $1450^{\circ}$ , all the mechanical properties alter suddenly. Further experiments were conducted on other samples of open-hearth steel, on Swedish steel, and on wrought iron. The results show that even a dead soft steel can be considerably hardened. The temperature to which it must be heated varies between the fusion point of nickel and the fusion point of dead soft steel—that is to say, between  $1450^{\circ}$  and  $1470^{\circ}$ . It might, *a priori*, be imagined that the hardening was due to a new critical point, but this was not borne out by the microstructure, which presented all the characters of normal martensite, while the changes resulting from annealing appear to be of the same nature as those which occur in more highly carburised hardened steels. The observed phenomena appear merely to indicate that the ordinary laws of hardening extend to mild steel in certain conditions. The critical temperature of hardening which, in the case of steels containing more than 0.3 per cent. of carbon, coincides with the point  $Ac_3$  or is a little higher, rises in the case of dead soft steel to the neighbourhood of the melting point, leading to the formation of a structure which is wholly martensitic, and shows neither troostite nor sorbite. In proportion as the carbon percentage in steel diminishes, and it approximates to pure iron, the critical temperature of hardening rises. Further experiments are to be undertaken to elucidate some of the points which still remain obscure.

R. S. MacPherran and J. F. Harper, *Spheroidised Cementite in Hypoeutectoid Steel* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 340–374). The paper gives the results of the authors' experience in the heat treatment of large forgings. The object of the investigation was to increase the ductility of forgings, especially the ductility, transversely or radially to the direction of forging. The method as developed was by spheroidising the cementite of the pearlitic constituent of the hypoeutectoid steels. It would appear from the experiments that the maximum ductility is obtained by the following procedure: A grain-refining treatment is used to secure the best dispersed pearlite and ferrite areas of the smallest size. This usually consists of heating to above the  $Ac_3$  point. Depending upon the forging or casting conditions, this treatment may be preceded by a normalising treatment. The spheroidising is then accomplished by moderately long heating (five to eight hours) at or slightly below the  $A_{c1}$  point for the steel as a whole and cooling in air. It is found that when the cementite of the pearlitic constituent is spheroidised, the tensile properties taken in various directions in reference to the line of work in forgings or to the surface in castings tend to become the same. The transverse and radial ductility is greatly increased by the treatment. Within reasonable limits the effect of forging reduction upon the ductility of transverse, longitudinal, and

radial tests is eliminated. The distortion which takes place in pearlitic steels with ageing or low temperature variations is reduced to a minimum when the cementite of the pearlite constituent is spheroidised.

*The Heat Treatment of Carbon Gun Steels* (Woolwich Research Department, 1920, Report No. 48). The investigation described in this report was carried out on carbon steel of the type used in gun construction, and was undertaken: (a) to determine the effect of high, medium, and low temperatures of hardening and tempering, and the influence of different rates of cooling from temperatures both above and below the critical range. (b) To correlate the microstructure with the heat treatment received and with the resulting mechanical properties.

*The Heat Treatment of Nickel Gun Steel* (Woolwich Research Department, 1921, Report No. 49). This report, which forms an extension of the work on carbon gun steels described in Report No. 48, deals chiefly with the correlation of the microstructure with the heat treatment received, the effect of different rates of cooling through the critical range, of high tempering temperatures and of rate of cooling from the tempering temperature, and on the mechanical properties, including results of notched-bar impact tests.

G. L. Thirkell, *Rock-Drill Steel Problem in Australia, with some Suggested Steps to its Solution* (Proceedings of the Australasian Institute of Mining and Metallurgy, December 1923, No. 52, pp. 79-128). The author has investigated the causes of rock-drill steel failures in the Australian mining industry, and makes a number of suggestions for the proper selection and treatment of the steel used for rock-drills.

N. H. Aall, *Softening of an Austenitic Nickel Steel* (Stahl und Eisen, September 4, 1924, vol. 44, pp. 1030-1031). The martensitic structure of a nickel steel containing carbon 0.65 and nickel 13.7 per cent. obtained by heating to 600° C. and quenching can be changed by annealing for two hours at 300° into an osmonditic structure which is easily machinable. If the structure contains austenite it must first be rendered martensitic before treatment to change it to osmondite. The lowest degree of hardness which can be produced in such a steel in the osmonditic condition is about 330 on the Brinell scale.

A. M. Parkin, *The Effect of Heat Treatment and of Variable Carbon Content on a Tungsten Magnet Steel of Fixed Tungsten Composition* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 1-46).

J. H. Nelson, *The Forging of Automobile Crankshafts* (Forging, Stamping, Heat-Treating, September 1924, vol. 10, pp. 312-317). The author gives a general description of the practice followed in the design, forging, testing, and heat-treating crankshafts for automobiles.

G. C. Davis, *Heat-Treating High-Speed Steel Dies* (Forging, Stamping, Heat-Treating, September 1924, vol. 10, pp. 360-362). Describes practice in the heat treatment of blanking dies of high-speed steel, which do not lend themselves to grinding after treatment.

C. G. Lutts, *Effect of Proofing and Annealing on Brittleness in*

*Large Chain Links* (Paper read before the American Society for Testing Materials, June 1924). Wrought iron chain links in the proofed state and in the annealed state were tested for resistance to shock. The tests indicate that the practice of proofing renders the chain links brittle and that such links break with a sharp and short fracture under shock. This brittleness may be removed by annealing.

E. K. Smith, *Hardened and Tempered Malleable Castings* (Transactions of the American Foundrymen's Association, 1923, vol. 31, pp. 295-312). The change in structure of malleable castings under varying heat treatments is shown by means of a number of photomicrographs.

*Annealing, Hardening, and Tempering by the Electrical Process* (Machinery, May 29, 1924, vol. 24, pp. 263-265). Particulars are given of the Lecfur method of heat-treating wire and strip. The essential principle of the system is the method of heating. This is effected by the passage of low voltage alternating current through the material, which itself is used as a conductor, the ohmic resistance acting against the flow of the current producing the requisite temperature.

W. Fraenkel and E. Heymann, *Kinetics of Annealing Processes in Steel* (Zeitschrift für anorganische allgemeine Chemie, 1924, vol. 134, pp. 137-171). The reactions which occur in quenched carbon steels during annealing have been investigated by means of resistance and density measurements.

P. E. McKinney, *Problems of the Heat Treater as Influenced by the pre-Natal History of the Material* (Transactions of the American Society for Steel Treating, July 1924, vol. 6, pp. 51-65). The author points out that while there have been exhaustive studies made in drawing up specifications for high-grade carbon and alloy steels in the direction of chemical and physical properties, not enough attention has been given to the methods used in melting and refining practice. Numerous photomicrographs showing typical structures observed in both normal and defective materials are incorporated in the paper.

M. A. Grossmann, *Manufacturing and Heat-Treating Alloy Steel* (Iron Trade Review, July 17, 24, 1924, vol. 75, pp. 168-172, 215-218). The author deals with the development of the alloy steel industry, the uses of alloy steels, methods of manufacture, and the factors influencing the heat treatment of alloy steels.

J. W. Urquhart, *Heat Treatment of Steel with Special Reference to Production* (Machinery, May 22, July 17, August 21, September 4, 1924, vol. 24, pp. 230-233, 497-499, 649-652, 709-712).

C. H. Fulton, H. M. Henton, and J. H. Knapp, *Heat-Treating: Its Principles and Applications* (Iron Trade Review, 1924, vols. 74 and 75). A continuation of a series of articles dealing with all the important phases of heat treatment. The following chapters have been recently published:

Hardening and Tempering (May 15, 1924, vol. 74, pp. 1309-1312).

Carburising and Case-hardening (May 29, June 12, 26, vol. 74,

pp. 1434-1437, 1560-1562, 1687-1689; July 10, 24, vol. 75, pp. 105-107, 223-225).

Heat Treatment of Alloy Steels (August 7, 21, September 4, vol. 75, pp. 355-358, 487-489, 595-598).

Electric Furnaces (September 11, vol. 75, pp. 673-675).

*Heat-Treating at the Chevrolet Plant* (Iron Age, July 17, 1924, vol. 114, pp. 129-131). Continuous combination furnaces are used by the Chevrolet Motor Co., Detroit, for the heat treatment of automobile shafts. The furnaces are of the double-deck type with the drawing chamber above the hardening chamber. Waste heat from the hardening chamber is utilised for the drawing chamber. Work passes through the hardening chamber into the quenching tank, and at the back of the furnace an elevator delivers it to the drawing furnace. The combustion chamber is located between the hardening and drawing chambers, making a combination over-fired furnace for high temperature and an under-fired furnace for low heats.

H. L. Read, *Operation Costs of Reheating Furnaces Reduced* (Iron Age, June 26, 1924, vol. 113, pp. 1865-1866). Brief particulars are given of the use of coke-oven gas for firing and reheating furnaces at an American plant.

R. H. MacGillivray, *Electric Furnace for Continuous Hardening and Tempering Wire* (Paper read before the American Electrochemical Society, October 1924). The electric furnace has proved to be an economical factor in the hardening and tempering of steel wire. Even distribution of heat, with absolute control of temperature, insures a uniformly satisfactory product and few or no rejections.

A. I. Nutting, *Electric Furnace Annealing* (Iron Age, August 14, 1924, vol. 114, p. 377). An analysis is given of fuel and labour costs in the operation of an electric annealing furnace.

J. Sorenson, *System as Applied to the Control of Furnace Temperatures and Heat Treatment of Automobile Truck Parts* (Transactions of the American Society for Steel Treating, July 1924, vol. 6, pp. 77-83). The author reviews in a general way the necessity of applying an adequate control system in the inspection of raw material for automobile truck parts, and their subsequent heat treatment. He discusses briefly a control system for the identification and accurate heat treatment of parts in process.

E. F. Collins, *The Metallic Resistor in Industrial Heating Furnaces* (Chemical and Metallurgical Engineering, June 16, 1924, vol. 30, pp. 936-941). An illustrated article dealing with the application and design of electric resistance heaters, with special reference to the use of metallic resistors. Examples are given showing how this type of equipment is applied to heat treatment, japanning and other furnaces. The conditions governing the use of the metallic resistor type of furnace are also discussed.

J. F. Harper and H. J. Stein, *The Microscope as a Control Instrument in Annealing Steel Castings* (Paper read before the American



Foundrymen's Association, October 1924). The solidification of medium carbon steels is briefly explained, and a number of photomicrographs are given showing the changes in structure due to varying heat treatments.

H. J. French and O. Z. Klopsch, *Quenching Diagrams for Carbon Steels in Relation to some Quenching Media for Heat Treatment* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 251-294). The paper deals with quenching diagrams for carbon steels containing from 0.25 to 1.25 per cent. carbon. In these are shown the relations between the Rockwell hardness, microstructure, thermal transformations and the cooling velocity determined at 720° C. A discussion is included covering the general relations between the quenching diagrams and various quenching media for heat treatment, such as water at different temperatures, oils, sulphuric acid solutions of various concentrations, brines and sodium hydroxide solutions. A selected bibliography relating to quenching media and the hardening of carbon steels is given.

H. Scott, *Quenching Properties of Glycerin and its Water Solutions* (Transactions of the American Society for Steel Treating, July 1924, vol. 6, pp. 13-32). The author has investigated the cooling power of glycerin and its water solutions as well as that of an oil and water emulsion, in an endeavour to find quenching media to span the gap between water and oil. From observations of experimental quenching curves giving the rate of cooling at the centre of a 1-inch diameter cylinder of 32 per cent. nickel steel, an alloy showing no transformations, but having approximately the same thermal properties as austenitic high-carbon steel, it is shown that glycerin-water solutions accomplish this purpose effectively, and moreover have characteristics distinctive from those of oil. The observations on the cooling rates of the baths were confirmed by observations of the hardening of deep-hardening steel in the several baths. The hardness of these steels, measured by the scleroscope and Rockwell tests increased definitely with the cooling rate, and the high hardness of the faster cooled steel was maintained on tempering below 300° C. By mathematical analysis of the results the cooling constants of the several baths were approximately evaluated and curves plotted from which the cooling rate at the centre and diameter gradients from centre to convex surface of large cylinders of any diameter can be estimated under certain limitations.

S. Tour, *Salt Baths* (Transactions of the American Society for Steel Treating, August 1924, vol. 6, pp. 171-186). The author gives the results of practical experience in the use of salt baths for heat-treating. Salt baths for the heat treatment of tool steels, design of furnaces for the proper melting of salt baths, and the composition of various salt mixtures are discussed.

**Drawing, Cold-Working, and Stamping.**—*British Wire-Drawing and Wire-Working Machinery* (Engineer, July 18, 25, August 1, 8, 1924,



vol. 138, pp. 72-74, 109-112, 130-131, 164-166). Modern wire-rod mills and wire-drawing machines are illustrated and described, and an account is given of the manufacture of wire rod and steel wire. The processes of annealing, patenting, pickling, coating with ferrie hydrate, dipping and baking are described. The baking at 100° C. removes the brittleness resulting from the pickling operation.

G. F. Comstock, *Wire-Drawing and Properties of Steel* (Iron Age, September 11, 18, 1924, vol. 114, pp. 621-624, 705-707). The author has studied the effects of progressive cold-drawing on the strength of steel.

M. Farmer, *Production of Cold-Rolled Strip Steel* (Forging, Stamping, Heat-Treating, August 1924, vol. 10, pp. 295-297). The author describes the manufacture of cold-rolled strip steel.

*Continuous Cleaning of Strip Steel* (Iron Age, May 8, 1924, vol. 113, pp. 1358-1359). Particulars are given of a continuous cleaning machine for removing the scale from hot rolled strip steel before cold-rolling. The strip is drawn through a row of large pickling vats by means of a take-up frame which re-winds it on blocks in its original coil form. There is a row of five cleaning vats in series which contain dilute sulphuric acid. Following the acid vats there is a cold water vat and hot water vat in which the acid is cleaned off. After leaving the last vat the strip passes through a gas-heated drying chamber and on to the drums of the take-up frame upon which it is coiled. The coils are then transferred to the cold-rolling department. Auxiliary lime and oil tanks are provided so that, if desired, the strip can be coated with lime or oil for shipping. The cleaning machine is in operation at the plant of the Trumbull Steel Company, Warren, Ohio.

F. Körber and W. Rohland, *Influence of Additions of Alloy Metals and of Temperature Changes on the Cold-Working Capacity of Metals* (Mitteilungen aus dem Kaiser-Wilhelm Institut für Eisenforschung, 1924, vol. 5, pp. 55-68).

J. D. Knox, *Operates New Cold-Drawing Plant* (Iron Trade Review, August 14, 1924, vol. 75, pp. 423-427). An illustrated account of the plant of the Anchor Drawn Steel Company, Pittsburgh, for the manufacture of cold-drawn steel. Primary annealing of the steel in coil form is carried out in gas-fired lead pots.

W. C. Chancellor, *Manufacture of Seamless Steel Tubing* (Proceedings of the Engineers' Society of Western Pennsylvania, July 1924, vol. 40, pp. 217-248). The author describes the manufacture of seamless steel tubes as carried out by the Mannesmann process at the Ellwood Works of the National Tube Company. The operations necessary for the production of hot-rolled tubes and cold-drawn tubes are described in detail, with observations on the structure and properties of the material as affected by the cold-drawing and annealing of the tubes.

A. J. Hain, *Shoenberger Works* (Iron Trade Review, August 21, 1924, vol. 75, pp. 475-479). An illustrated account is given of the

development of the Shoenberger Works of the American Steel and Wire Company, Pittsburgh. The plant was the first to be established west of the Allegheny Mountains for the manufacture of finished iron products. It is the oldest unit among all of the subsidiaries of the United States Steel Corporation. The only finished products at the present time are horseshoes. The plant was established in 1824.

**Railway Tires.**—*The Manufacture of Railway Tires* (Engineer, May 30, 1924, vol. 137, pp. 602–603). The article describes the manufacture of steel tires as practised in Sheffield sixty years ago. The first tire rolled from a solid block appears to have been made by Charles Bartholomew and John Heppenstall, who in 1857 took out a patent for machinery for rolling tires and hoops for railway and other wheels. There is reason to believe that the first weldless steel tires were made from crucible steel, but when the Bessemer process became established Bessemer steel soon superseded all other material for the manufacture of tires. The difficulties in working the converter so as to get the correct temperature and composition were very great, as the means for readily controlling the operations were not then available as they are now. A standard composition was aimed at, of which particulars are given. About 1882 a demand for higher tensile strength arose, and this was obtained by increasing the percentage of manganese and adding about 0.5 per cent. of chromium.

**Gun Manufacture.**—T. Tanimura, *Improvements in Gun Construction and Allied Problems* (Journal of the Faculty of Engineering, Tokyo Imperial University, March 1923, vol. 13, No. 4, pp. 103–184). The paper deals especially with the strength of relined guns. The erosion of gun tubes is quite without remedy at present, so that gun construction which renders relining most easy is worth while studying as a policy of salvage. From calculations of the strength of relined guns, it is found that the inner surface of the bore of the relined gun is always subjected to a stress beyond the elastic limit. It is shown that the ordinary method of designing a gun to facilitate its relining is entirely wrong in principle. The self-shrinking process seems to be an ideal method of gun construction, and two new methods which have some advantages over the existing methods have been proposed by the author.

**Welding.**—R. Devillez, *Autogenous Welding by the Electric Arc* (Revue Universelle des Mines, December 15, 1923, vol. 19, pp. 407–412). A brief account of the history and methods of electric welding.

A. Hochstimm, *Electric Arc Welding* (Zeitschrift des Vereines deutscher Ingenieure, February 9, 1924, vol. 68, pp. 129–132). The principles and the process of electric arc welding are fully described, and the type of apparatus suitable for various kinds of work is indicated.

H. C. Price, *Electric Welding of Large Storage Tanks* (Paper read

before the American Institute of Mining and Metallurgical Engineers, February 1924). The paper describes in a general way the electric welding of the sheets forming the roofs and bottoms of large oil storage tanks, and discusses the advantages of electric welded tanks over those of riveted construction.

*Oxy-Acetylene Welding in the Process Equipment Field* (Chemical and Metallurgical Engineering, September 1, 1924, vol. 31, pp. 341-346). The application of oxy-acetylene welding and cutting in the production and repair of chemical equipment is described and illustrated.

A. H. Jansson, *Describes Welding Process* (Foundry, June 1, 1924, vol. 52, pp. 442-443). The use of a welding compound for the welding of grey and malleable iron castings is dealt with. The principal constituent of the compound is stated to be a specially prepared iron powder mixed with other chemicals, which have the tendency to absorb the carbon from the cast iron, to toughen the metal, and to eliminate excessive oxidation. Cast iron may be welded at a comparatively low temperature. The results of tests on welds made with the use of this compound are given.

J. G. Pearce, *The Welding of Cast Iron from a Metallurgical Point of View* (Paper read before the British Acetylene and Welding Association: Foundry Trade Journal, July 24, 1924, vol. 30, pp. 78-79). The factors influencing the weldability of cast iron are discussed, and it is pointed out that the weldability in general, and the success with which it can be undertaken in particular cases, depends entirely upon its constitution, and is essentially a metallurgical problem.

R. Trautshold, *Spot-Welding for Pressed Steel Parts* (Forging, Stamping, Heat-Treating, July 1924, vol. 10, pp. 265-266). Practice in spot-welding is described and its advantages over riveting are compared.

H. Y. Carson, *Welding Iron Pipe with Bronze* (Paper read before the National Gas Association of America: Iron Trade Review, July 10, 1924, vol. 75, pp. 97-98; Foundry, June 15, 1924, vol. 52, pp. 469-470). The use of tobin bronze for the welding of cast iron is briefly dealt with. It is shown from tests that the bronze has three times the tensile strength of cast iron. Only moderate temperatures are required in welding cast iron with tobin bronze.

*Design of Welds* (Iron Age, May 8, 1924, vol. 113, pp. 1361-1363). At a recent meeting of the American Welding Society, a number of short papers were presented outlining the authors' views on the question as to whether a weld in a structure should be designed more rigid or more flexible than the parts which it joins. Papers were presented by the following, short extracts of which appear:

J. C. Lincoln, "Carbon Arc-Welding."

S. W. Miller, "Gas Welding."

C. J. Holslag, "Metal Arc-Welding."

H. A. Woofter, "Resistance Welding."

J. H. Depper, "Thermit Welding."

**Pickling.**—C. A. Edwards, *Pickling: the Action of Acid Solutions on Mild Steel, and the Diffusion of Hydrogen through the Metal*. (This Journal, p. 9.)

V. S. Polansky, *Pickling of Iron and Steel: A Bibliography* (Forging, Stamping, Heat-Treating, July, August, September 1924, vol. 10, pp. 267-269, 298-301, 350-354).

**Tin-Plating.**—W. Krämer, *Tinning Machines* (Stahl und Eisen, June 19, 1924, vol. 44, pp. 713-715). The operations involved in the tinning of sheets are described, and two tinning machines, the Abercarn and the Thomas and Davies, are illustrated.

**Galvanising.**—H. Bablik, *A Study of Fluxing in Galvanising* (Metal Industry, June 6, 1924, vol. 24, pp. 541-543). The author has studied the mechanism of sal-ammoniac as a fluxing agent in galvanising.

W. M. Peirce, *The Preece Test for Zinc-Coated Materials* (Iron Age, July 24, 1924, vol. 114, pp. 199-201). The author criticises the value of the Preece test, in which a copper sulphate solution is used for the testing of zinc coatings on iron and steel. Results are given of tests which show that the Preece test does not give comparable determinations of the weights of coating on galvanised coatings having dissimilar surfaces or structures, though it may have some value for indicating the uniformity of a coating.

**Coating of Metals by Spraying.**—T. H. Turner and W. E. Ballard, *Metal Spraying and Sprayed Metal* (Paper read before the Institute of Metals, September 1924). The appliances and operation of the metal spraying process, the nature of sprayed metal coatings, the building up of solid articles by spraying, and the efficiency and applications of the process are discussed. The process is at the present time used in France and Germany to a considerable extent on shipping work, and for the protection of overhead transmission line poles and wireless masts. It is being increasingly used in this country for the protection of certain portions of ships and for propellers. It was largely used in Germany during the war for protecting shell parts from corrosion. Other uses include the coating of steel vulcanising pans, the tinning of tanks intended for foodstuffs, and the coating of oil containers with zinc or aluminium. Another use of the aluminium coating is that of protecting iron from oxidation at high temperatures. Two methods are available—the first and best being that of spraying aluminium on to the iron at a red heat after it has previously received a very thin coating in the cold state. The second method is by spraying the aluminium cold and then transforming some of the metal into oxide by the use of chemical reagents.

*Metallisation* (Machinery, August 21, 1924, vol. 24, pp. 641-644). An illustrated description of the applications of the Schoop metal spraying process.

**Enamelling.**—B. Rewald, *Use of Antimony in the Enamel Industry* (Chemiker-Zeitung, May 1, 1924, p. 280). The use of glazes and frits containing antimony are suitable for enamel ware, even for food containers. According to the author, there is no justification for the legal prohibition of the use of antimony for enamel ware.



## PHYSICAL AND CHEMICAL PROPERTIES.

**Properties and Tests of Cast Iron.** —R. Kühnel and E. Neesemann, *The Structure of High Quality Grey Cast Iron* (Stahl und Eisen, August 28, 1924, vol. 44, pp. 1042-1044). High quality grey cast iron with a strength of 18 kilogrammes per square millimetre contains only the three constituents—pearlite, graphite, and phosphide eutectic. Ferrite, if present at all, is only to be found in minute traces, and cementite cannot be detected. The phosphide eutectic, hitherto known also as ledeburite, has sometimes been mistaken for cementite in specimens not properly etched. It is proposed that this constituent in future shall be designated "phosphide eutectic" to the exclusion of any other name, since the percentage of phosphorus in the iron largely determines the amount and distribution of the phosphide eutectic. Ancient iron castings, which were broken up for scrap in the war, proved to be extraordinarily tough, and on examination were found to consist of pearlitic iron and to have a chemical composition similar to that of high quality castings with a strength of 18 kilogrammes. Analysis showed that they contained not more than 0.57 per cent. silicon and 0.06 per cent. phosphorus.

H. Jungbluth, *A Means for Distinguishing Cementite or Ledeburite from Phosphide Eutectic* (Kruppsche Monatshefte, June 1924, vol. 5, pp. 95-98). In ordinary cast irons phosphide eutectic appears in a form closely resembling ledeburite or secondary cementite. The author has made trials of several etching reagents with a view to finding one which will differentiate these two constituents of cast iron. Matwieff had previously found that neutral or alkaline picrate of soda would fulfil this purpose, and the author's experiments confirm Matwieff's work. The neutral picrate solution must, however, be prepared from the solid picrate salt and not by neutralising a solution of picric acid in water.

F. Rogers, *The Nature of Phosphide Eutectic* (Foundry Trade Journal, September 4, 1924, vol. 30, p. 194). A photomicrograph is given which shows the phosphide eutectic in grey cast iron at 5000 diameters. This reveals that the constituent, which appears as dark markings at 1000 diameters and is commonly described as iron carbide, is actually duplex, and, in fact, very similar to pearlite, consisting of alternate laminae of iron carbide and iron. It is recognised from the research of Stead that there would be present the three constituents of the triple eutectic, namely, iron phosphide, iron carbide, and austenite, or their transformation products. Thus the presence of

laminated pearlite, from the transformation of austenite, is accounted for. The pearlite thus associated structurally within the phosphide eutectic masses may conceivably be richer or poorer than obtains in the normal pearlite ratio.

L. Northcott, *The Formation of Graphite in Cast Iron* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, June 19, 1924, vol. 29, pp. 515-521). The author deals with the effect of annealing white cast iron at different temperatures and under such conditions as to produce temper carbon or nodular graphite, and describes experiments of a typical grey cast iron to determine the mechanism of the formation of flaky or primary graphite. The paper is illustrated with numerous photomicrographs.

T. Turner, *Some Effects of Casting Temperature and Rate of Cooling on the Properties of Metals and Alloys* (Proceedings of the Cleveland Institution of Engineers, Session 1923-24, pp. 219-237).

E. J. Lowry, *The Effect of Chill on Cast Iron* (Paper read before the American Foundrymen's Association, October 1924). The result of experiments shows that the deposition of elements varies with the casting temperature and rate of cooling. An investigation of chilled rolls and car wheel iron was also carried out to verify the experimental results. It is concluded that in ordinary chill irons the chill rejects the chemical elements from the chilled surface of any iron poured in contact with it. Sulphur upsets the normal "solidifying rejections" when it is in increased percentages over the regular run of cast irons.

H. A. Schwartz and Mrs. A. N. Hird, *Chemical Equilibria during Solidification and Cooling of White Cast Iron* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1925). The authors have studied the distribution of silicon between austenite and cementite during and after freezing, by analysing the cementite of various samples of white cast iron separated by the electrolytic solution of the austenite. Incidental information was obtained, also, with respect to the distribution of manganese, silicon, and phosphorus, when only relatively small amounts of each are present. It is concluded that during the freezing of the ternary system iron-carbon-silicon, the silicon will be rejected to the liquid phase and will all be found in the eutectic cementite, if the cooling is slow enough to permit the attainment of equilibrium. Whether this silicon exists as silico-cementite, or as a separate structure of silicide, interlacing with the cementite, the authors are unable to state.

A. Hayes, W. J. Diederichs, and H. E. Flanders, *The Mechanism of Graphitisation of White Cast Iron and its Application to the Malleabilising Process* (Paper read before the American Foundrymen's Association, October 1924). The authors describe an investigation carried out at the Iowa State College which, in combination with the results obtained by other investigators, resulted in a theory for the mechanism of the complete graphitisation of white cast iron. It is

stated that the precipitation of the first ferrite about the primary carbon spot is due to two factors: (1) The carbon spot promotes the precipitation of carbon, and (2) it acts as an inclusion to promote the separation of ferrite. Eutectoid action after the ferrite envelope is completed takes place by the deposition of ferrite upon that already in the shell, while the carbon is precipitated throughout, forming the small carbon spots. These carbon spots may therefore be considered as evidence of an eutectoid structure. The formation of the ferrite shell around the primary carbon spots produces the well-known "bull's eye" structure. This mechanism leads to the belief that complete graphitisation could be brought about in much shorter periods than those now in use commercially. It is also indicated that a whole series of intermediate products of graded physical properties could be produced by only minor variations in the annealing treatment. It is also shown that if carbon is once deposited in poor form, subsequent treatment will prove of no appreciable value in correcting it.

E. Piwowsky, *The Effect of the Presence of Titanium in Castings Subjected to Malleabilising* (Stahl und Eisen, June 26, 1924, vol. 44, pp. 745-748). The author has previously shown that the properties of ordinary grey iron castings undergo considerable improvement by a small addition of titanium (Stahl und Eisen, December 6, 1923, vol. 43, p. 1491). The present investigation was undertaken to determine in what way the malleabilising process would be affected by the presence of titanium in castings made from a pig iron of the following composition: carbon 3.38, silicon 0.49, manganese 0.45, and sulphur 0.15 per cent. The iron was melted in an electric resistance furnace, and titanium was added in the form of ferro-titanium containing 20.9 per cent. titanium and 0.15 per cent. carbon. For purposes of comparison three sets of specimen bars were cast—one containing no titanium, the second with 0.089 per cent., and the third with 0.12 per cent. titanium. Micrographs of the material before and after annealing are shown. It was found that titanium promoted the formation of a fine structure in the casting before annealing, and in the malleabilised casting the temper carbon was uniformly in a very fine state of division. The dissociation of the carbides was effected more rapidly in the case of the titanium-treated metal. The effect of titanium is more marked in the black-heart process than in the castings annealed with red hæmatite.

F. Sauerwald, H. Allendorf, and P. Landschütz, *Density and Expansion of Liquid and Solid Grey Pig Iron* (Zeitschrift für anorganische Chemie, 1924, vol. 135, pp. 327-332). The density of a pig iron which was practically of a eutectic composition was determined. The solid metal showed a mean specific volume of 0.1460 (density = 6.85) at 700°, which rose to a maximum of 0.1484 (density = 6.73) at 840°, and then decreased steadily as the melting point was approached. At melting point a sharp decrease took place, followed immediately by a rapid increase on liquefaction. The abnormal contraction on melting

is probably due to the formation of large quantities of cementite in the melt, and the maximum in the specific volume curve is attributed to the formation of cementite and  $\gamma$ -iron mixed crystals.

R. Buchanan, *The Problem of the Liquid Contraction in Grey Cast Iron* (Paper read before the Foundry Trades Exhibition Congress : Foundry Trade Journal, July 3, 1924, vol. 30, pp. 11-12). The author reviews the phenomena of liquid contraction in cast iron and summarises the conclusions of previous investigators.

R. T. Rolfe, *Some Cooling Effects in Cast Iron and their Correction* (Metal Industry, May 23, 30, June 6, 1924, vol. 24, pp. 501-502, 525-526, 551-552). The author discusses the general causes giving rise to internal stresses in castings, and methods of relieving them. Particulars are also given of an investigation of annealing temperatures.

E. Adamson, *Carbon in Cast Iron* (Transactions of the Manchester Association of Engineers, 1922-1923, pp. 125-169). The author discusses the influence of carbon on the molecular physics of cast iron.

J. W. Bolton, *Structural Segregation in Grey Iron* (Iron Age, September 18, 1924, vol. 114, pp. 685-689). The author points out some of the normal structural segregations occurring in grey iron and semi-steel, and indicates the practical significance of their non-homogeneous structures. The segregations especially considered are those of graphitic carbon flakes. While the amount and size of these flakes are well known to affect the properties of the metal, their exact distribution and its significance have received little attention. Some consideration is given to the normal variations of pearlite and ferrite, and the effects of phosphorus distribution are explained.

J. W. Bolton, *Study Structure of Grey Iron* (Foundry, August 15, 1924, vol. 52, pp. 628-634). The author points out the limitations and the precautions necessary in the practical use of the microscope for the study of the structure of grey iron. As the distribution of graphite in cast iron is not uniform, a considerable area must be included in micrographs to obtain representative pictures. By means of a number of micrographs the author demonstrates the advantages and disadvantages of low and high power magnifications. Macrography is defined as the examination of a polished or an etched surface by visual inspection or at low magnification. The American Society for Testing Materials approves up to 10 diameters as limiting macrography. In low power microscopic methods the author includes work up to 50 diameters.

E. Maurer, *A Cast Iron Diagram* (Kruppsche Monatshefte, July 1924, vol. 5, pp. 115-122). The author shows a diagram on which carbon and silicon percentages are plotted as ordinates and abscissæ respectively, by means of which he has produced a cast iron, as far as possible independent of the cooling conditions, showing a pearlitic ground mass with a fine structure and having excellent tensile properties.

G. W. Gilderman, *Testing Iron to Control the Properties of Castings* (Paper read before the American Foundrymen's Association, October



1924). The author discusses some of the factors that tend to make test-bars unreliable.

J. W. Bolton, *Notes on Composition and Structure of A.S.T.M. Bar* (Paper read before the American Foundrymen's Association, October 1924). The author shows the effects of variation in composition and structure on the properties of the standard A.S.T.M. cast iron test-bar.

J. T. Mackenzie, *The Standard Test-Bar for Cast Iron Pipe, with Special Reference to its Progressive Deflection* (Paper read before the American Society for Testing Materials, June 1924). The author has investigated the elongation and transverse strength of test-bars representing cast iron for use in pipe manufacture. The bars were of widely different analyses and origin.

R. Moldenke, *Recent Investigations on Cast Iron for Pipe* (Paper read before the American Society for Testing Materials, June 1924). The author gives the results of an extended investigation of the testing of cast iron. It was found that with present-day material and practice the existing specifications for cast iron pipe were too difficult to meet generally. Operating tests to improve the metal by varying mixtures also failed to give the desired results. Test curves are given for various bars used. The relationship of composition and strength of cast iron is discussed.

C. O. Bannister, *Cast Iron as an Engineering Material* (Transactions of the Liverpool Engineering Society, 1923, vol. 44, pp. 304-314). The causes of variation in composition and the mode of occurrence and influence of the various elements in cast iron are discussed. Methods for improving the quality of castings are also summarised.

W. Rother, *Strength of Cast Iron and its Thickness* (Iron Age, August 7, 1924, vol. 114, pp. 326-327). The author has investigated the relationship between the physical characteristics and the thickness of iron castings. The results of tests show approximately 11 per cent. decrease in strength for each  $\frac{1}{2}$  inch increase in thickness.

A. Marks, *Porosity in Cast Iron* (Foundry Trade Journal, July 10, 1924, vol. 30, pp. 25-27). The causes and means for the prevention of porosity in castings are discussed.

T. E. Hull, *Growth of Grey Cast Iron* (Foundry, April 1, 1924, vol. 52, pp. 253-254). The first growth of cast iron is due to occluded gases, which, being liberated under pressure, cause deformation of the graphite crystals, thus opening up avenues for the entrance of oxygen to the iron. The second stage of growth is due to oxidation of iron silicide. As the point of maximum growth is approached some free iron is oxidised.

J. H. List, *Cold Laps in Cast Iron* (Foundry Trade Journal, August 21, 1924, vol. 30, p. 166). The causes of cold lap in castings are briefly discussed.

**Properties and Tests of Wrought Iron and Steel.**—R. Mailänder, *Fatigue Phenomena and Endurance Tests* (Stahl und Eisen, May 22, 29,



June 5, 12, 19, 1924, vol. 44, pp. 585-589, 624-629, 657-661, 684-691, 719-725). The author presents a general review of the investigations of previous workers into the phenomena of fatigue, and of the development of various methods of carrying out endurance tests, beginning with the work of Wöhler and Bauschinger down to the present time. The second article of the series illustrates and describes a large number of apparatus devised for the performance of endurance tests. An extensive bibliography on the subject of fatigue phenomena and vibration tests is appended at the end of the series.

H. W. Gillett and E. L. Mack, *Notes on Some Endurance Tests of Metals* (Paper read before the American Society for Testing Materials, June 1924). The authors present the results of an extended investigation on the endurance testing of alloy steels and non-ferrous metals carried out by the United States Bureau of Mines. Static and impact tests with both single and repeated applications of stress were used in the investigation. The injurious effect of inclusions is emphasised, and the effect of various factors upon the endurance strength of metals is pointed out. An appendix is included containing over fifty references to literature on the fatigue of metals.

H. F. Moore and T. M. Jasper, *Fatigue of Metals* (University of Illinois, Engineering Experiment Station, Bulletin No. 142, May 26, 1924, 86 pp.). This constitutes the third report on the progress of the investigation. The authors modify and extend the theory that fatigue failures in metals start from slip planes within the crystalline grains. Specimens of wrought irons and steels which had previously been subjected to millions of cycles of stress without failure, on retesting showed an increase of resistance to further repeated stress. Previous reports are contained in Bulletins 124 and 136 of the Engineering Experiment Station. The present report covers two nickel steels, ingot iron (0.02 per cent. carbon), steels containing 0.045 to 1.20 per cent. carbon, copper, brass, bronze, and Monel metal, and a number of heat treatments of various steels. A bibliography of the literature on fatigue of metals published since the issue of the last report is appended.

F. S. Merrills, *Studies in the Fatigue of Metals* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 83-128). The author has studied the effect of structure on the endurance of metals subjected to repeated stresses, and deals with the amorphous cement theory and the effect of cold-work on the endurance of metals.

J. G. R. Woodvine, *The Behaviour of Case-Hardened Parts under Fatigue Stresses* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 197-237). The results of the investigation indicate that a substantial increase may be expected in the fatigue-resisting properties of a case-hardening steel with an increasing proportion of nickel up to 6 per cent. The moduli of elasticity of the material of the case and of the core are practically identical, and may be taken as such with confidence.

P. Oberhoffer and W. Oertel, *The Recrystallisation of Electrolytic*

*Iron* (Stahl und Eisen, May 15, 1924, vol. 44, pp. 560-561). Commercial irons show a maximum grain size after a 10 per cent. deformation at a temperature between 700° and 800° C. Electrolytic iron, on the other hand, does not recrystallise to a maximum grain size under the same conditions, and it is supposed that this difference in behaviour is to be ascribed to the absence of impurities in the electrolytic iron. Carefully conducted experiments with purest electrolytic iron have confirmed the observation that a 10 per cent. deformation at the critical temperature does not produce a maximum grain-growth in the pure iron, but the grains continue to grow very slowly as the deformation is increased. The impurities in the commercial iron must therefore account for the difference in behaviour.

W. Riede, *Recrystallisation Phenomena in Steels Subjected to Alternating Stress Tests* (Stahl und Eisen, July 24, 1924, vol. 44, pp. 880-883). Specimens of silico-manganese steels, chromium steels, nickel-chromium, and carbon steels were subjected to rapidly alternating stress tests, and the changes in structure were noted. These changes differ in amount according to the degree of alternating stress to which the material is subjected.

D. J. McAdam, jun., *Accelerated Fatigue Tests and Some Endurance Properties of Metals* (Paper read before the American Society for Testing Materials, June 1924). The paper describes a method of investigating the endurance properties of metals by the "accelerated fatigue method." The test is an actual breakdown test, and the saving of time effected will be of great advantage. Results of endurance tests on steel and non-ferrous metals by the accelerated method and by the slower methods are presented. The paper also presents the results of an investigation of the torsion endurance range of steel.

D. J. McAdam, jun., *The Endurance Properties of Corrosion Resistant Steels* (Paper read before the American Society for Testing Materials, June 1924). The author describes the results of an investigation to determine the relation of endurance properties to the results of the more common mechanical tests. The endurance tests were made by the rotating cantilever method and by the alternating torsion method.

F. C. Lea and H. P. Budgen, *The Effect of High Temperature on the Range of Repetition Stresses on Steel* (Paper read before the British Association, Toronto, August 11, 1924; Engineering, October 3, 10, 1924, vol. 118, pp. 500, &c.). The authors describe experiments carried out in order to determine the ranges of stress for various mean stresses that certain steels would withstand when tested under 2000 cycles per minute, and at temperatures varying from 15° to 800° C.

*Effect of Sulphur on Endurance Properties of Rivet Steel* (Third Preliminary Report presented to the American Society for Testing Materials, June 1924). Endurance tests were carried out on fourteen heats of rivet steel, the sulphur ranging from 0.03 to 0.08 per cent. All tests were made upon rivet bar material  $\frac{9}{16}$  inch in diameter—that is, with the axis of the specimen parallel to the direction of rolling. The

bars were tested in the annealed and quenched state. The results of the tests are shown graphically. The relationship of the endurance limits to other physical properties is also recorded.

*Metallographic Investigation of Effect of Sulphur on Rivet Steel* (Fourth Preliminary Report presented to the American Society for Testing Materials, June 1924). The results are given of an extensive metallographic investigation of rivet steel, including the study of the microstructure by means of sulphur prints, an investigation of non-metallic inclusions, and a study of the microstructure as affected by various heat treatments. Decided differences between steels of various sulphur content that had received the same heat treatment led to an investigation of the microstructure at high magnifications of 1000 and 4000 diameters, the results of which are included.

R. R. Moore, *Resistance of Metals to Repeated Static and Impact Stresses* (Paper read before the American Society for Testing Materials, June 1924). The paper gives the results of tests to determine the endurance limits of some ferrous and non-ferrous metals, the effect of a notch and of cold-working on these endurance limits, and the resistance of these metals to impact stresses. A comparison of endurance limits with other physical properties is made. The metals tested included carbon steel, vanadium steel, and stainless iron.

J. R. Cain, *Influence of Sulphur, Oxygen, Copper, and Manganese on the Red-Shortness of Iron* (Paper read before the American Electrochemical Society, October 1924). The influence of these elements on the red-shortness of pure iron and Armco iron was investigated in a series of small experimental ingots. The ingots were melted under vacuum, or in an induction furnace under air. Bars forged from these ingots were tested for red-shortness by bending over a blacksmith's anvil, while they cooled from approximately  $1100^{\circ}$  to  $500^{\circ}$  C. It was found that in order to avoid red-shortness not more than 0.01 per cent. of sulphur should be present. Oxygen in amounts up to 0.20 per cent. does not cause red-shortness in pure iron if the sulphur is below 0.01 per cent. Manganese may prevent red-shortness in iron when present to the extent of three times the sulphur percentage, if the oxygen percentage is not over 0.04. The presence of considerable amounts of oxygen in irons (0.10 per cent. and above) tends to reduce the efficiency of manganese in preventing red-shortness. The hypothesis is advanced that this is because some of the manganese is present as oxide. Copper (0.05 to 0.5 per cent.) is of minor importance in its effect on red-shortness of pure iron, but in some of the specimens it tended to decrease the red-shortness.

M. A. Grossman, *Brittle Range in Low-Alloy Steels* (Iron Age, July 17, 1924, vol. 114, pp. 149-151). The brittle range existing in steels containing a low percentage of alloying element is discussed. It is shown by the author that this phenomenon is due to the fact that a small amount of austenite is retained as a structural constituent when the steel is quenched. This austenite is stable up to certain drawing

temperatures, but is then broken up, more or less completely, depending on the temperature and the time of drawing. The resultant brittle submicroscopic alpha iron interspersed throughout the remaining steel microstructure would account for the brittleness. The results of tests on chrome-molybdenum steel are given in which the brittle range was observed by dilatation methods.

Belanger, *Special Brittleness of Notched Steel Bars after Impact in the Notch* (Revue de Métallurgie, May 1924, vol. 21, pp. 312-314). It was noticed that in breaking up old rails for charging in an open-hearth furnace it was customary at a certain works to cut a notch through the rail head and then to strike the bottom of the notch, whereupon the rail broke much more readily than if any other method was adopted. This was thought to be worthy of investigation, as it appeared to indicate that the brittleness of a notched bar was greatly increased by the blow on the bottom of the notch. As the result of experiments, this was found to be the case, although the effect of a hammer blow on an unnotched bar was negligible. This type of brittleness is evidently little known of at present. Any such manipulation should be carefully avoided in workshop practice.

H. S. Rawdon and S. Epstein, *The Nick-Bend Test for Wrought Iron* (United States Bureau of Standards, 1924 : Technologic Paper No. 252). The nick-bend test is included in nearly all specifications for wrought iron, the character of the fracture of a nicked bar being the criterion by which the material is judged. A coarsely crystalline fracture is generally considered as indicative of inferior material. The majority of American specifications are very indefinite regarding the manner by which the specimen is to be broken, and permit any method between slowly applied pressure and a single-blow impact stress. The authors describe an investigation which was carried out upon eight different grades of wrought iron, and one of open-hearth iron, which were fractured under different conditions and the character of the fracture was studied. The crystallinity of the fracture depends upon the size and distribution of the slag threads in the wrought iron. The rate at which the specimen is fractured also affects the character of the break, and when broken by severe impact crystallinity usually results. The same material broken by bending usually shows a fibrous fracture. The results of the investigation show that the test cannot be depended upon to show the presence of "steel" in wrought iron nor to give results by which the phosphorus content may be judged. In short, in many specifications the nick-bend clause is meaningless and should either be eliminated or redefined.

W. Oertel and L. A. Richter, *The Influence of Size of Ingot and Hot Deformation on the Properties of a Nickel Chromium Structural Steel* (Report No. 4 of the Laboratory of the Glockenstahlwerke A.G., Remscheid, 1924, 5 pp.). In the routine testing of nickel-chrome steel, containing 4.5 per cent. nickel and 1 to 1.5 per cent. chromium, considerable discrepancies in the results of tests were noted, more



especially in the notch toughness of specimens taken across the grain of the forging. As the cross-section of the bars and the heat treatment were the same in all cases, it was supposed that the size of the original ingot and the varying degree of forging in the hot state must have some influence on the nature of the finished forging, and reference is made to the work of Charpy, Descolas, and others on this same question. A series of experiments was carried out at the laboratory at Remscheid on four ingots of different sizes to determine what the effect of the ingot size and degree of forging would be. The results confirmed the observations of others, namely, that the specific work of rupture is very greatly affected by the degree of deformation in the hot state. The more the piece is drawn out under the hammer, the higher is the specific work of rupture in longitudinal bars, but that of bars cut transversely is lowered. The spreading of a forging under the hammer, however, produces just the opposite effect. The influence of the ingot size diminishes according as the cross-section is reduced by forging. The changes in notch toughness are attributable to the development and changes in the primary fibrous structure due to deformation in the hot state.

P. Ludwik, *The Significance of the Elastic Limit, Elongation, and Notch-Toughness for the Structural Engineer* (Zeitschrift für Metallkunde, June 1924, vol. 16, pp. 207-212). The usual methods of testing the mechanical properties of materials are discussed and explained. The tensile test alone is an insufficient criterion, and the measurement of the limit of elasticity is difficult to carry out with accuracy. To get trustworthy results the tensile test, in conjunction with the notched-bar impact test, should be used.

G. Welter, *The Dynamic Method of Measuring the Elastic Limit of Metals and Alloys* (Zeitschrift für Metallkunde, June 1924, vol. 16, pp. 213-220). In continuation of his previous paper (Ibid., January 1924, pp. 6-11), the author has worked out a new method for determining the elasticity of metals by an impact tensile test. A drop machine is used and readings are taken with a modified form of Martens' mirror apparatus, which is clamped to the test-bar and will register a permanent elongation as small as 0.001 millimetre. Theoretically, the dynamic elastic limit should agree with the static, but in practice the elastic limit as determined by dynamic methods lies considerably higher than that determined by the use of a static load. The dynamic method, however, gives more accurate results.

R. H. Smith, *High Tensile Strengths of Low Carbon Steels* (Paper read before the American Society for Testing Materials, June 1924). It is shown that the properties of steels (carbon under 0.15 per cent.) are greatly affected by heat treatment. It is possible to obtain a tensile strength of 90,000 lbs. per square inch and higher without brittleness.

H. P. Troendly and G. V. Pickwell, *A New Theory on Overstrain and Strength of Materials* (Transactions of the American Society for Steel Treating, August 1924, vol. 6, pp. 145-170). The authors present a résumé of the various theories relating to elastic and plastic



deformation and the mechanism of slip. They have evolved a new theory on the mechanics of overstrain and strength of materials, which might be termed "the plastic transfer of the proportional elastic range." They conclude from the evidence which they review and the new data they submit that any strengthening as the result of cold-work is not through the formation of a hard amorphous material which renders the section deformed of higher elementary unit-strength, but that the increase in strength in any direction is at the expense of the strength in the opposing direction. Also that the increase in strength in the direction of overstrain is through a mechanism of slip whereby more of the elementary areas or units are allowed to slip into position to assume higher stress in the direction of overstrain.

T. M. Jasper, *The Calculation of Quenching Stresses in Steel by Using Direct Measurements* (Paper read before the British Association, Toronto, August 12, 1924; Engineering, September 5, 1924, vol. 118, pp. 343-344). A description of a method of determining quantitatively the internal stresses set up by quenching and the distribution of these stresses in the cross-section of a series of heat-treated bars, together with a description of their relative importance, is presented. It appears that the elastic limit, or limit of proportionality, between stresses and strains in iron and steel, is largely dependent on initial quenching and subsequent treatment. This shows that the elastic limit is not a static property which should be used as a basis in design. The yield point, and failing this, the ultimate stress, is the best characteristic static property to use with a factor of safety consistent with the requirements of design.

J. Seigle and F. Cretin, *Elastic Limit and Tensile Strength of Annealed Mild Steels under Combined Tensile and Torsional Stress* (Comptes Rendus, July 21, 1924; Génie Civil, August 23, 1924, vol. 85, p. 178). The results of the authors' experiments lead to the conclusion that the safe load for mild steel material under torsional shearing stress is 60 to 65 per cent. that of the safe load of the same material under tensile stress.

P. Nicolau, *Calibration of Tensile Test Machines by means of Test-Pieces* (Revue de Métallurgie, June 1924, vol. 21, pp. 342-355). The usual method employed for calibrating a tensile testing machine is open to many objections, chief amongst which are its costliness, no less than twelve test-pieces being required, and sometimes more, and its lack of accuracy. The 4 per cent. tolerance allowed in such tests is too large. An alternative method employed at the Saint-Jacques de Montluçon Works has yielded far more satisfactory results. Two groups of test-pieces are cut from the same homogeneous mild steel and made into two sets of test-pieces of respectively different diameters, one set being tested on the standard machines to maximum breaking strain, and the other set being distributed to other observers, with the data derived from the first set of tests. Actual experiment has established that with reasonable care the tolerance need not, in such cases,

exceed 0.35 per cent., while the whole process can be greatly cheapened. Details of the method and of the results are given.

F. Cretin and J. Seigle, *Some Results of Shearing Tests on Steel Cable Wires* (Revue de l'Industrie Minérale, Mémoires, December 1, 1923, pp. 667-674). An account of tests on the shearing strength and general behaviour of various kinds of drawn steel wire employed in the manufacture of wire ropes and cables.

J. Seigle, *Some Observations on the Effects of Permanent Torsion on Steels* (Comptes Rendus, 1924, vol. 178, pp. 2062-2065). Steel bars were subjected to permanent deformation by torsion and the outer cylindrical layers were then removed by acid attack. When these were dissolved the inner layers tended to straighten, though complete recovery from the twisted condition was never attained. The change in length through twisting beyond the elastic limit was measured.

J. Seigle and F. Cretin, *Torsion Tests of Metals; Elastic and Permanent Deformation* (Génie Civil, June 7, 14, 1924, vol. 84, pp. 545-549, 565-568). Cold-worked and annealed steels were subjected to torsion tests, and the results are plotted in the form of diagrams. The torsional limit of elasticity, reduction of area, and behaviour of the individual layers of material were noted.

L. Aitchison, *The Low Apparent Elastic Limit of Quenched or Work-Hardened Steels* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1923, vol. 12, pp. 113-217).

L. Aitchison, *Some Fundamental Defects of Hardened Steels* (Transactions of the American Society for Steel Treating, May 1924, vol. 5, pp. 491-503). With the exception of plain carbon steels that contain less than 0.35 per cent. carbon, all steels when in the fully hardened state have certain definite properties which can be regarded as being defects. These defects, or some of them, are found in steels that have been hardened either by cold-working or quenching. One adverse property of these steels is the abnormally low value of the limit of proportionality. This is found in both quench-hardened and work-hardened steels, but the cause of its presence in the two types of steel is not identical. The existence of the low value of the limit of proportionality in quenched steels is connected definitely with the stresses that have been endured by the steel during the actual quenching operation. It seems that wherever any austenite is present in the steel—even in quite small quantities—a low value of the limit of proportionality is found. The limit of proportionality of all fully hardened steels is raised by reheating. The quenched and air-hardened steels give the highest value of the limit of proportionality when tempered at a temperature between 350° to 400° C. Naturally such a treatment reduces the maximum stress from the fully hardened value, so that this treatment cannot be applied in the event of the high-maximum stress being necessary. In the cold-worked steels the cause of the low value of the limit of proportionality is to be found in the changes brought about in the steel during the working process. There

seems to be little doubt that the low elastic limit in such steels is the result of the slipping induced in the ferrite of the steel during the cold-working. A cold-worked steel can be reheated safely to the proper temperature for producing a high value of the elastic limit without thereby losing its strength or hardness. Values of limit of proportionality in different hardened steels are given, and it is shown that there is a very large difference between the actual stress which produces some permanent deformation in the steel and the stress which is generally called the yield point. Another defect that is found in quenched steels, and particularly in those that when quenched acquire a high maximum stress, is instability of volume. The fundamental aspect of this problem is also discussed.

F. Körber and W. Rohland, *The Elastic Behaviour of Cold-Worked Steel* (Mitteilungen aus dem Kaiser-Wilhelm Institut für Eisenforschung, 1924, vol. 5, pp. 37-54). Experiments were carried out to determine the influence of the degree of cold-working and ageing on the elastic behaviour of steel, and the effect of the duration of cold-stretching on the capacity of different carbon steels to recover their original length. In the light of the phenomena observed, an explanation of the behaviour of cold-worked steel when subjected to elastic tests is given.

W. P. Sykes, *Tensile Properties of some Steel Wires at Liquid Air Temperatures* (Transactions of the American Society for Steel Treating, August 1924, vol. 6, pp. 138-144). The author has compared the tensile properties of low-carbon steel, nickel steel, and chrome-molybdenum steel as measured at room temperature and the temperature of liquid air (about  $-180^{\circ}\text{C}.$ ). The steels, in the form of wire, were tested in tension as annealed, as water-quenched, and as quenched and tempered at four temperatures between  $300^{\circ}\text{C}.$  and  $700^{\circ}\text{C}.$  Maximum tensile strength was found in the chrome-molybdenum steel either as hardened, hardened and tempered, or annealed when tested at  $-180^{\circ}\text{C}.$  Maximum ductility, indicated by elongation and reduction of area, was shown by the nickel steel after hardening and tempering at  $700^{\circ}\text{C}.$  The nickel steel possessed throughout the highest elongation of the three steels tested.

W. Rosenhain, *Present Position of the Theories of the Hardening of Steel*. (This Journal, p. 145.)

J. Cohade and E. Schneider, *Comparative Tests on Hardness of Various Tool Steels when Heated* (Revue Universelle des Mines, January 15, 1924, vol. 1, pp. 75-104). The object of the investigation was to ascertain the comparative hardness, when heated, of three typical tool steels: a carbon steel, a tungsten steel, and a high-speed chromium-tungsten-vanadium steel, and to find out the reasons for the superior cutting properties of the latter. It was sought likewise to study the influence of the quenching temperature and heat treatment on the hot-hardness of certain high-speed steels and to establish a relationship between the heat treatment, the hot-hardness, and the cutting properties.

The conclusions arrived at were as follows: The hot-hardness (at 550° C.) of the high-speed tools tested increases steadily in proportion as the temperature of quenching becomes higher, up to 1350° C., and such quenchings confer a partial austenitic structure on the steels. It is the transformation of the austenite into martensite which, at about 600° to 650° C., produces the secondary hardening. Above 1200° high-speed steels have a wholly martensitic structure, have a lower hot-hardness, and do not display secondary hardening. The best cutting properties are developed by quenching from very high temperatures (1300° to 1350° C.). In regard to steels containing tungsten, the hot-hardness increases slightly with the percentage of tungsten. Hot-hardness, measured by the ball test, however, is a variable property even for the same steel, and cannot alone be used to determine the comparative utility of different high-speed steels.

H. Schottky, *Hardness of Iron Nickel Alloys* (Zeitschrift für anorganische allgemeine Chemie, 1924, vol. 133, pp. 26-28).

S. L. Hoyt, *The Ball Indentation Hardness Test* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 396-420). The author discusses Meyer's analysis of the ball indentation test, and shows the manner in which such an analysis can be applied to certain fundamental problems in hardness testing.

E. G. Herbert, *Work-Hardening of Various Metals* (Iron Age, June 19, 1924, vol. 113, pp. 1792-1793). The application of the Herbert pendulum tester for the investigation of the work-hardening of various metals is discussed.

C. Benedicks and V. Christiansen, *Investigations on the Herbert Pendulum Hardness Tester*. (This Journal, p. 219. See also Jernkontorets Annaler, No. 7, 1924, vol. 108, pp. 361-393.)

A. Hultgren, *Improvements in the Brinell Test on Hardened Steel, including a New Method of Producing Hard Steel Balls*. (This Journal, p. 183. See also Jernkontorets Annaler, No. 9, 1924, vol. 108, pp. 453-494.)

A. Vierendeel, *The Phenomenon of the Cold-Working of Iron and Steel* (Génie Civil, June 28, 1924, vol. 84, pp. 630-631).

R. Arrowsmith, *A Note on the Effect of Grain-Size on the Extension at the Yield Point in Armco Iron*. (This Journal, p. 317.)

E. Marcotte, *New Process for Preventing the Wear of Rails and Tires* (Arts et Métiers, January 1924, vol. 77, pp. 5-21). This question, the importance of which is becoming more and more recognised, was the subject of discussion at the International Rail Congress, held in Rome in 1922. The axle load in the case of locomotives has now reached as much as 33 tons, and speeds have likewise increased. Such progress as has been made in steel rails during the last few years has been in the direction of increasing the section and improving the chemical composition of the metal and its method of heat treatment. Increasing the section has not proved satisfactory, but the addition of alloy metals to the steels has had better results. In America titanium has been



used, but the so-called titanium steel rails do not contain any of that element, which is really added solely as a deoxidiser. Nickel steel rails are too costly, but manganese steel rails are currently used. High-carbon steel rails are too brittle, and high-silicon steel rails suffer from the same disadvantage, although in certain circumstances silicon can with advantage be added, provided the carbon be kept low. The progress in heat treatment is discussed, but the problem is complicated by the fact that a rail requires to be hardened in order to prevent wear, and yet not hardened sufficiently to render it brittle. The various factors which have to be taken into consideration are grain-size, and structure. The experience gained during the war in the manufacture of steel shells has thrown considerable light on the structure suitable for metal intended for rails. In this connection the Sandberg process has yielded very satisfactory results. Such rails have a sorbitic structure, and are now being very largely employed. A further advantage of the process is that it can be readily applied in the existing plant, and does not need the installation of special mills. Tables are given of some of the actual results obtained in practice, both in regard to impact resistance and to hardness. Sorbitic steel is now being used in the manufacture of tires as well. The paper is accompanied by numerous photographs.

J. H. Hall and G. R. Hanks, *Composition and Physical Properties of Cast 12 per Cent. Manganese Steel* (Paper read before the American Society for Testing Materials, June 1924). The paper gives the average composition of manganese steel, with brief comments on the proper limits for the different metalloids and a summary of methods of manufacture employed in foundries. Heat treatment, metallography, and the physical properties, including tension and bending tests, shear, hardness, resistance to wear, fatigue resistance, coefficient of expansion, heat and electrical conductivity, and magnetic properties are also summarised.

Sir Robert Hadfield, *Modern Trackwork and its Importance* (Paper read before the Institute of Transport, Sheffield 1923). The application of manganese steel for rails and trackwork is discussed.

*Spring-Testing Machine for Railway Rolling Stock* (Iron and Coal Trades Review, July 4, 1924, vol. 109, p. 18). Particulars are given of an Avery testing machine for the testing of laminated and coil springs used on railway rolling stock. The machine described has a maximum loading capacity of 20 tons, and vibratory tests can be carried out in addition to deflection tests.

J. S. G. Primrose, *Dynamometers* (Paper read before the Manchester Association of Engineers, January 25, 1924). The paper reviews some of the more modern types of dynamometers.

C. Frémont, *The Mechanical Testing of Steel Tubes* (Études Expérimentales de Technologie Industrielle, Mémoire No. 65, Paris 1923, 52 pp.). The author illustrates and describes the methods ordinarily in use for testing steel tubes, and prescribes new methods of testing



which will enable the more accurate determination of the tensile strength, elongation, brittleness, hardness, and purity of the metal.

T. W. Greene, *Strength of Steel Tubing under Combined Column and Transverse Loading, including Tests of Columns and Beams* (United States Bureau of Standards, 1924, Technologic Paper, No. 258).

G. Pigeaud, *Strength of Steel Cables* (Génie Civil, April 12, 19, 26, May 3, 1924, vol. 84, pp. 345-351, 374-378, 399-402, 421-423). The author deals more particularly with cables for suspension-bridges, giving mathematical calculations for determining their strength and conditions of equilibrium.

H. L. Whittemore and A. H. Stang, *Tests of some Girder Hooks* (United States Bureau of Standards 1924, Technologic Paper, No. 260).

A. de Marneffe, *Note on the Influence of the Method of Piercing Holes in Steel Bars* (Revue Universelle des Mines, April 1, 1924, vol. 2, pp. 42-48). Deals with the loss in tensile strength of metal plates which have had holes punched in them as compared with plates in which the holes have either been drilled or punched, and subsequently reamed out to a wider diameter. The latter is by far the best method. Experiments showed that from the point of view of safety, holes should not be punched, unless they are subsequently reamed, as this serves to remove areas which, having been subject to severe shearing stresses, remain strained and a source of weakness.

C. Benedicks, D. W. Berlin, and G. Phragmen, *A Method for the Determination of the Specific Gravity of Liquid Iron and other Metals of High Melting Point* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 129-166. See also Jernkontorets Annaler, No. 6, 1924, vol. 103, pp. 308-333). Iron with low carbon contents, containing originally 0.10 per cent. carbon, which, however, in the course of the experiment is estimated to have increased to 0.2-0.3 per cent., was found to have a specific gravity at 1550° C. of  $6.92 \pm 0.07$ .

O. Hengstenberg, *The Density of Iron-Silicon Alloys and their Relation to the Phase Diagram* (Stahl und Eisen, July 31, 1924, vol. 44, pp. 914-915). It is shown that the silicon contents of iron-silicon alloys may be approximately estimated by measurement of the specific volumes of the alloys.

J. H. Andrew and A. J. K. Honeyman, *The Specific Volume of Steels* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 253-266). The values obtained by the authors for the specific volume of iron and of cementite, and the double iron-chromium-carbide found in annealed nickel-chromium steels, show that the measurement of the specific volume affords a convenient and ready method of investigating the changes produced in steel by thermal treatment.

L. Aitchison and G. R. Woodvine, *Changes of Volume of Steels during Heat Treatment*. (This Journal, p. 275.)

M. Jakob, *New Tests on the Heat-Conductivity of Liquids, Insulating*

*Materials, and Metals* (Chaleur et Industrie, February 1924, vol. 5, pp. 62-65). An account of a new apparatus and method for estimating thermal conductivity. The experiments described relate, for the most part, to tests made on the conductivity of nickel steel containing 30 per cent. of nickel. This material has a remarkably low conductivity which renders it specially useful in many industrial and scientific applications.

P. Chevenard, *Dilatometric Analysis of Alloys, with Special Reference to Cast Iron* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, July 3, 1924, vol. 30, pp. 3-10). The dilatometric method for the physical analysis of solid bodies presents, unlike the electrical and magnetic methods, the advantage of distinct sensitiveness to secondary reaction, such as impurities, thermal history, and other phenomena which are unable to mask the essential facts. The author deals with the technique of dilatometric analysis and reviews some of the results obtained with cast iron.

D. W. Berlin, *Determination of the Coefficient of the Dilatation of Tungsten* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 167-174).

**Specifications.**—J. O. Roos af Hjelmsäter, *Nomenclature in Connection with the Testing of Tensile Strength of Metals, Standard Tensile Test-Pieces for Iron and Steel, Specifications for Forgings for Machine Parts and for Steel Castings* (Jernkontorets Annaler, 1924, vol. 108, pp. 404-450).

*Dimensions and Properties of British Standard Rolled Steel Sections for Structural Purposes* (British Engineering Standards Association, 1924, Report No. 6). The revised edition of this Report includes the values of the geometrical properties of all the British Standard Steel Sections for structural purposes in all the standard thicknesses. For the convenience of designers a series of approximate formulæ has been added by which the geometrical properties of intermediate sizes of the standard sections, standard sections having web thicknesses other than those given in the lists, or sections of similar proportions to the standards, can be obtained. Metric equivalents of the standard dimensions, areas, and other geometrical properties, and the calculated weights of the sections are also given.

*British Standard Specification for Galvanised Steel Wire Strand for Signalling Purposes* (British Engineering Standards Association, 1924, Report 163).

*British Standard Schedule of Valve Steels and Valve Forgings for Automobiles* (British Engineering Standards Association, 1924, Report 5008).

*British Standard Dimensions for Narrow Type Concentric Piston Rings for Automobiles* (British Engineering Standards Association, 1924, Report 5023).

*Interim British Standard Specification for Iron Castings for Air-*

*Cooled and Jacketed Cylinders for Automobiles* (British Engineering Standards Association, 1924, Report 5024).

*British Standard Schedule of Wrought Steels for Automobiles* (British Engineering Standards Association, 1924, Report 5005).

*British Standard Schedule of Sheet Steels for Automobiles* (British Engineering Standards Association, 1924, Report 5007).

*British Standard Schedule of Steel Tubes for Automobiles* (British Engineering Standards Association, 1924, Report 5009).

*Interim British Standard Specification for Iron Castings for Sand-Cast Pistons and Valve Guides for Automobiles* (British Engineering Standards Association, 1924, Report 5025).

*Interim British Standard Specification for Iron Castings for Fly-wheels for Automobiles* (British Engineering Standards Association, 1924, Report 5026).

*Report of Committee A1 on Steel* (American Society for Testing Materials, June 1924). This Report contains a number of proposed revisions in certain standard and tentative specifications for steel, issued by the American Society for Testing Materials.

*Report of Committee A2 on Wrought Iron* (American Society for Testing Materials, June 1924). This Report contains the revisions of standards for wrought iron, and the proposed revised tentative specifications for iron and steel chain.

*Report of Committee A4 on Heat Treatment of Iron and Steel* (American Society for Testing Materials, June 1924). Particulars are given of the proposed revised tentative recommended practice for heat treatment of carbon-steel castings.

**Magnetic Properties of Iron and Steel.**—E. H. Crapper, *The Elements of Magnetic Analysis* (Engineering, April 11, May 9, 23, June 20, 27, 1924, vol. 117, pp. 452–454, 601–602, 660–662, 786–788, 816–817). The author endeavours to evolve a system for determining the exact values of magnetic constants by magnetic analysis. The magnetic properties of a sample of steel are fixed by its constitution, which is the resultant of the composition and physical treatment to which it has been subjected; consequently there must be some definite relation between the magnetic and other physical properties of the material. Since the effects of thermal and mechanical treatment upon the magnetic properties may be determined experimentally without destruction of the test-pieces, there is a distinct advantage in this method.

L. Guillet, *The Hardening of High-Speed Tool Steels, and their Electrical Resistivity* (Revue de Métallurgie, October 1923, vol. 20, pp. 656–664). Although numerous investigations on the composition, heat treatment, use, and constitution of high-speed tool steels have from time to time been carried out, one of the properties best calculated to elucidate hardening phenomena—namely, the electrical resistance of the steels—has hitherto been ignored. The present research bore upon the influence of hardening temperature, annealing

temperature, and duration of heating period prior to quenching upon the electrical resistance. The steel was a complex one, containing 0.65 per cent. of carbon, 18.20 per cent. of tungsten, 3.60 per cent. of chromium, and 0.80 per cent. of vanadium. It was found that the electrical resistance increased the longer the period of heating and the more markedly the higher the temperature. Heating to 1200° C. for 2 minutes was equivalent to heating to 1100° for 20 minutes. The temperature influence was therefore obvious. From the point of view of the hardness it was found that this increased with the increase in the period of heating, when a temperature of 900° C. was employed. At 1000° heating for 10 to 20 minutes had the same result. At 1100° the hardness decreased as the hardening temperature increased, and at 1200° the hardness remained constant after 10 minutes' heating. The hardness after annealing is greater than on quenching if the quenching temperature is above 1100° C.

S. R. Williams, *Hardness of Steel Balls by Magnetic Tests* (Transactions of the American Society for Steel Treating, May 1924, vol. 5, pp. 479-484). The paper describes a rapid method for determining magnetically the hardness of steel balls. The arrangement of the apparatus used by the author is shown, and the results of tests on balls of different hardness are included.

L. Fraichet, *The Magnetisation of Steel Produced by Tensile Stress* (Génie Civil, May 24, 1924, vol. 84, pp. 495-498). The author describes a magnetic method of testing steel specimens and recommends the use of it as complementary to the ordinary tensile test.

R. L. Sandford, *The Present Status of Magnetic Analysis* (Transactions of the American Society for Steel Treating, June 1924, vol. 5, pp. 577-589). Reference is made to the numerous types of testing equipment which have been developed in the study of special shapes and types of material. The author also reviews the history of magnetic studies of various investigators, and points out the advantages and disadvantages of this method of testing. The paper includes a bibliography of the literature on magnetic analysis published during the period 1914-1924.

R. Cazaud, *The Annealing of Sheets used in Electrical Constructions* (Comptes Rendus, May 12, 1924; Revue de Métallurgie, August 1924, vol. 21, pp. 473-483). In electrical machines, magnetic circuits subjected to very wide variations in flux are built up of thin sheets which must possess: (1) high magnetic permeability; (2) a low and uniform hysteresis; (3) high resistivity; and (4) a minimum thickness compatible with workshop operations. The kind of sheets employed comprise: (1) dead soft steel with carbon below 0.10 per cent.; and (2) special steels containing the same amount or less of carbon and from 1 to 5 per cent. of silicon. The silicon steel affords, in greater degree than mild steel, the qualities required, and possesses the further advantage of not "ageing," and therefore preserves them unchanged by the efflux of time. It is found that cold-working reduces the per-



meability and increases the hysteresis losses, and such sheets, rolled or worked cold, possess but indifferent properties, which are susceptible of very considerable improvement on annealing. A number of tests were carried out to ascertain the best conditions for the annealing of such sheets. The steel in question contained 2.85 per cent. of silicon. It was found that, on annealing at 450° C., improvement set in. Above this temperature, both maxima and minima were encountered in regard to hysteresis losses, and above 800° the magnetic properties deteriorated. The permeability was invariably greater in the direction of rolling, and lower in the transverse direction. The influence of duration of annealing was likewise investigated. The results of the experiments are recorded in tables and plotted as diagrams. The broad conclusions derived from the research were: (1) that annealing is indispensable; (2) that a maximum of the desired qualities is developed at about 800° C., irrespective of the silicon content; (3) that annealing should last at least two hours, and that no improvement could be found after more than ten hours' annealing; (4) that air-cooling after annealing was to be recommended, to avoid deterioration in the quality; and, finally, (5) that annealing should be carried out in a reducing atmosphere.

M. A. Hunter and A. Jones, *Some Electrical Properties of High Resistance Alloys* (Paper read before the American Society for Testing Materials, June 1924). The specific resistances and temperature coefficients of high resistance alloys at high temperatures are summarised. The alloys discussed are divided into three groups: Material of high resistance for use at temperatures below 500° C., having nickel as their major constituent; materials of high resistance for use at temperatures above 500° C., including alloys which are essentially combinations of nickel, iron, and chromium, in various proportions; and materials having special properties which render them useful under restricted conditions, such as the high temperature coefficient of electrical resistance of pure nickel and the remarkably low temperature coefficients of some alloys. The attempt to use high resistance alloys as elements in base metal thermocouples for the measurement of temperature was a natural step in the development of these alloys, and some information has therefore been included in the paper on the electromotive force which may be expected from various combinations of these materials.

E. D. Campbell and G. W. Whitney, *A Laboratory Method for the Preparation of Small Steel Bars Differing only in Carbon Content, and the Effect of Changes in Carbide Concentration on the Specific Resistance* (Transactions of the American Society for Steel Treating, July 1924, vol. 6. pp. 32-50). The authors give a brief description of a laboratory method by means of which small steel bars, varying only in carbon content, may be prepared, and also the results of specific resistance measurements on some such bars when annealed and when hardened by quenching in oil or water. By systematic application of the



principles involved in carburisation by means of carburising mixtures, decarburisation with moist hydrogen and equilibration in dry hydrogen at  $950^{\circ}\text{C}$ ., the authors prepared four series of steels, comprising 38 compositions with carbon contents ranging from 0.0 to 1.75 per cent. Specific resistance measurements were made of annealed, oil-hardened, and water-hardened round bars and of square bars in both annealed and oil-hardened conditions. The specific resistance observed for the nearly pure iron carbon series in the annealed conditions are, it is thought, nearer to those which may be found for strictly pure iron carbon alloys than any other values so far published.

E. D. Campbell and G. W. Whitney, *The Effect of Changes in Total Carbon and in the Condition of Carbides on the Specific Resistance and on Some Magnetic Properties of Steel*. (This Journal, p. 291.)

A. W. Smith, E. D. Campbell, and W. L. Fink, *Effect of Changes in Total Carbon and in the Condition of Carbides on the Magnetic Properties of Steel* (Physical Review, 1924, vol. 23, pp. 377-385). Magnetisation curves are given for two series of steels, prepared from Armco iron and from a 2.23 per cent. chromium steel, to show the variations in magnetic properties with the carbon content. The minimum reluctivity  $R$  is found to be a linear function of the carbon content for hardened steel up to 0.8 per cent. carbon. For annealed carbon steel  $R$  increases somewhat faster than the percentage of carbon, and for annealed chromium steel  $R$  shows a maximum at about 0.5 and a minimum at about 0.8 per cent. carbon. The magnetic intensity necessary for saturation varies in the same way as  $R$ . A magnetic potentiometer method of determining normal magnetisation curves for short bars is described.

F. Stäblein, *The Influence of Combined Carbon on the Specific Resistance of Iron* (Zeitschrift für Physik, 1923, vol. 20, pp. 209-228). The specific resistances of seventeen steels, with carbon varying from 0.05 to 1.65 per cent., were measured by a compensation method. The higher resistances of these steels as compared with pure iron is caused by the formation of iron carbide. The resistance of pure iron was found to be 10.0 microhms per cubic centimetre, which agrees with the results of Gumlich and others. The specific resistance of cementite is calculated to be 70 to 80 microhms per cubic centimetre, and experimental results by the author give the value 95 microhms per cubic centimetre.

W. V. Mayneord and A. A. Dee, *Some Thermo-Magnetic Properties of Nearly Pure Iron* (Physical Society of London, May 23, 1924). Experiments were carried out with Armco iron and with rods of annealed iron and cold-drawn iron wires.

S. W. J. Smith, A. A. Dee, and W. V. Mayneord, *The Magnetism of Annealed Carbon Steels* (Physical Society of London, May 23, 1924). It has already been shown that the residual moment of a magnetised rod of annealed steel of definite dimensions does not diminish continuously towards zero as the temperature is raised,<sup>a</sup> but changes

sign at about  $180^{\circ}\text{C}.$ , reaches a maximum negative value at about  $220^{\circ}$ , and afterwards falls slowly until the temperature at which steel ceases to be ferro-magnetic is reached. This reversal is primarily due to the laminated structure of the carbide eutectoid which the steel contains, and it disappears when that structure is destroyed. Measurements were also made to determine the relationship of the intensity of the residual moment at  $220^{\circ}$  to the dimension-ratio of the bar, and to the intensity of the field by which it is magnetised.

E. A. Watson, *Cobalt Magnet Steels* (Paper read before the British Association, Toronto, August 13, 1924; Engineering, August 22, 29, 1924, vol. 118, pp. 274-276, 302-304). In a carbon-free iron-cobalt alloy the effect of adding cobalt is to produce an increase in the specific magnetism or intensity of magnetisation, up to a maximum of 35 per cent. cobalt, after which it again decreases. The effect of cobalt on the coercive force of a steel is very much greater than the effect on its saturation density, the coercive force being increased by three times for a cobalt content of 33 per cent. Analyses of magnet steels containing cobalt and other alloying elements, such as chromium, tungsten, and molybdenum, are given, with curves showing approximately the effect of cobalt on a given type of steel. Alloys with cobalt at 35 per cent. are difficult to forge, and in some series of alloys the cobalt cannot exceed 20 per cent. owing to the difficulty in hardening.

J. Šafráneck, *The Magnetisation of Nickel-Chromium Alloys above the Curie Point* (Revue de Métallurgie, February 1924, vol. 21, pp. 87-107). A physico-chemical investigation of the magnetic properties of the alloys dealt with, based on the paramagnetic theory of Langevin and the Curie law. Attempts have been made to introduce quanta considerations to displace the classic dynamo-static views in regard to diamagnetic and paramagnetic bodies. In regard to the magnetisation of ferro-magnetic bodies in functions of the temperature and field, Weiss's law takes the Curie constant into consideration, from which it follows that when a ferro-magnetic substance is heated to above the Curie point, the Curie molecular constant is the product of the molecular mass susceptibility (measured at a temperature above that of the Curie point), and the temperature difference observed at the temperature point taken. A number of experiments were carried out to ascertain whether this law holds good, the apparatus employed and the results of the experiments being illustrated and tabulated. Very pure nickel was obtained with 99.89 per cent. of nickel. Chromium was specially prepared at the author's laboratory by electrolysis from dissolved chromium sulphate. The nickel chromium alloys having thus been carefully prepared, it was found in the subsequent experiments that the Curie constant depended on the proportion of chromium present. The changes are reversible. A bibliography of the subject is given.

L.W. McKeehan, *Ferro-Magnetism and its Dependence upon Chemical, Thermal, and Mechanical Conditions* (Journal of the Franklin Institute,

May, June 1924, vol. 197, pp. 583-601, 757-786). A review is presented of the magnetic properties of the known ferro-magnetic metals and the principal agents which vary those properties, with a view to testing a new theory to account for the ferro-magnetism of iron, cobalt, and nickel.

A. E. Kennelly, *The Reluctivity of Permalloy* (Journal of the Franklin Institute, May 1924, vol. 197, pp. 623-627). Comparative magnetic tests of permalloy and Armco iron show that the permeability of permalloy is very much greater than that of soft iron.

S. E. Dawson, *Non-Magnetic Cast Iron* (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, May 29, 1924, vol. 29, pp. 439-444). The fundamental drawback of cast iron as applied to the electrical industry was that it was magnetic to a greater extent than any other metal, but this feature has now been overcome with the production of non-magnetic cast iron. The characteristics of this material are shown in comparison with ordinary grey cast iron and brass.

**Iron and Steel Alloys.**—*Ferrous Alloys Research*. (This Journal, p. 85.) Part 1: Introductory, by W. Rosenhain; Part 2: Iron and Oxygen, by F. S. Tritton and D. Hanson; Part 3: The Estimation of Oxygen in Pure Iron, by T. E. Rooney.

*Medium-Carbon High-Manganese Steels* (Woolwich Arsenal, Research Department Report, No. 61, London: H.M. Stationery Office). The report deals with the properties of medium carbon steels with high manganese content. The five steels used in the investigation were made by the crucible process. The carbon content ranged from 0.36 to 0.39, and the manganese content from 0.25 to 5.25 per cent. The steel containing the maximum manganese content could be forged with difficulty, but the surface was very imperfect, and showed numerous cracks. The steel with highest manganese content on which a complete series of tests was made contained 2.86 per cent. of manganese. A number of surface cracks were observed in this steel, and this manganese content appeared to be near the limit of useful composition. Heating and cooling curves were taken by the inverse-rate method, of samples of the four steels after normalising. The rate of heating employed was about 9° C. per minute. Cooling curves were taken from 800° C. and from 900° C. The conclusions arrived at were as follows: The critical points Ac1 and Ar1 are lowered by the presence of increasing amounts of manganese. Ac3 and Ar3 are lowered until they merge into Ac1 and Ar1 respectively. The presence of manganese tends to prevent the separation of ferrite and pearlite on cooling. The slowest permissible rate of cooling through the critical range to produce hardening and to suppress the separation of ferrite is much slower than that permissible for carbon steels. An increase in the initial temperature has little effect on the position of Ar1 or on the hardness of the treated steel. After oil-hardening and tempering at

650° C. all the mechanical properties of a 0.4 per cent. carbon steel are improved by the presence of about 2 per cent. manganese. The improvement in properties is still maintained with 2.86 per cent. of manganese, but the additional manganese shows no advantage and may introduce difficulties in forging. The steels with high manganese content are extremely liable to show temper-brittleness when slow rates of cooling after tempering are employed, but this may be avoided by suitable treatment. If good impact figures are to be secured, the cooling from the tempering temperature must never be slower than in air, and as the steels harden when quenched or quickly cooled from temperatures considerably below the beginning of A<sub>cl</sub> as usually determined, a tempering temperature higher than 660° C. should be avoided. For many purposes for which it is desired to replace carbon-steel forgings by steels of greater strength, the following composition may be suggested: Carbon, 0.35 to 0.40 per cent.; manganese, 1.8 to 2.2 per cent. Oil hardened from 800° to 850° C. Tempered from 610° to 650° C. Cooled in air, oil, or water.

M. A. Grossman and E. C. Bain, *On the Nature of High-Speed Steel*. (This Journal, p. 249.)

F. Rapatz, *Influence of Ledeburitic Constituents in the Production and Treatment of Tool Steels* (Stahl und Eisen, September 18, 1924, vol. 44, pp. 1133–1138). The double carbide which appears in high-class steels, especially in chromium and tungsten steels, corresponds closely with the ledeburite of pure iron-carbon alloys. It is proposed, therefore, to designate this class of steel “ledeburite steels.” The most important group of this class is the high-speed tool steels. The second group consists of the chromium steels with 1.4 to 14 per cent. chromium; the third of tungsten steels with from 4 to 6 per cent. tungsten; and the fourth group of carbon steels with over 1.7 per cent. carbon. Some notes on the characteristics and treatment of these steels are given.

W. Oertel and F. Pölguter, *Influence of Cobalt and Vanadium on the Properties of High-Speed Steel* (Stahl und Eisen, September 25, 1924, vol. 44, pp. 1165–1169). Comparative cutting tests are described, as carried out with cast and forged high-speed steel tools of different composition—namely, molybdenum steels, molybdenum-cobalt, molybdenum-vanadium, and molybdenum-cobalt-vanadium steels. Careful experiments were made to determine the quenching temperature best suited to produce the requisite degree of hardness in each class of steel. The material on which the tools were tested was in the form of open-hearth steel bars of 12-inch diameter, of a tensile strength of about 40 tons to the square inch, and the cutting speed was 17 metres per minute, the depth of cut 4 millimetres, and rate of feed 1.42 millimetres. The results, given in diagrams, show that the addition of cobalt and vanadium considerably increases the cutting durability, but the influence of the vanadium considerably preponderates over that of cobalt. In view of the high price of cobalt, there is practically little or no advantage gained by adding it, and vanadium, with



molybdenum or tungsten will give practically the same benefit as cobalt with vanadium.

*New Tool Steel Material* (Iron Age, August 21, 1924, vol. 114, p. 449). It is stated that a new crucible tool steel has been produced by the Dycast Steel Co., Collinsville, Connecticut. Special treatment is imparted to the steel in the crucible during melting. The steel is unusually quiet in the crucible and shows no sign of burning in spite of an exceptionally high temperature. After pouring it becomes plastic almost at once, and retains this plasticity for a considerable time before rapid solidification. No mention is made of the composition or the treatment used.

P. Chevenard, *Methods of Research and Verification in Accurate Metallurgy* (Mémoires de la Société des Ingénieurs Civils de France, July–September 1923, pp. 932–972). A description of the routine of discovering and rendering commercially available a new alloy, and of the methods employed for investigating its qualities, developing them and devising processes for its manufacture and treatment on an industrial scale. As examples, the work carried out at the Imphy Steelworks for investigating the properties of such alloys as invar, platinite, and elinvar is described. The properties dealt with are dilatation, electrical properties, and the moduli and coefficients of elasticity and of thermo-elasticity, and in each case the apparatus employed and the methods of testing are illustrated and explained.

E. H. Schulz and C. W. Drescher, *Stellite and Alloys of the Stellite Class* (Zeitschrift für Metallkunde, September, October 1924, vol. 16, pp. 337–343, 382–390). The properties and treatment of recently introduced alloys, in which iron is not the chief component element, are discussed. Besides stellite, reference is made in particular to K.S. magnet steel, permalloy, and a new alloy to which the name akrit has been given. The composition of this is about as follows: cobalt 38, chromium 30, tungsten 16, nickel 10, molybdenum 4, carbon 2 to 5 per cent. Comparative cutting tests on open-hearth steel railway axles showed that for rough cutting the akrit lasts  $2\frac{1}{2}$  times as long as ordinary high-speed steel, and for finishing cuts it outlasted the high-speed steel by 37 times at 32 metres per minute, and by 7 times at 50 metres per minute.

E. W. Pierce, *Molybdenum Steel—Some Productive Data* (Transactions of the American Society for Steel Treating, June 1924, vol. 5, pp. 571–576). A discussion of the physical properties of chrome-nickel and chrome-molybdenum steels. Particulars are included of the costs of machining connecting rods made from these steels, as a basis for determining the adaptability of these types of steels for automobile purposes.

J. B. Johnson and S. A. Christiansen, *Characteristics of Material for Valves operating at High Temperatures* (Paper read before the American Society for Testing Materials, June 1924). The paper describes the results of laboratory tests and single-cylinder and multiple-



cylinder engine tests of steels proposed for valve use. The valves referred to in the paper are of the poppet type, with either mushroom or tulip shaped heads. The tensile strength and hardness of valve stems at high temperatures are tabulated. The requirements demanded of steels for service in valves of aircraft engines are particularly severe. The metal must not only be proof against the chemical attack of the exhaust gases at temperatures as high as 1600° F., but must also be capable of withstanding the mechanical or eroding action of these gases impinging at high velocities on the junction of the head and stem, and "wire drawing" through the valve opening. In addition, the tensile strength should be high at operating temperatures, and it must be possible to make the metal in the stem capable of avoiding galling at the guides and to harden the tappet end sufficiently to prevent distortion due to the action of the valve-operating mechanism. No materials have been found to fulfil all of the above requirements. The quaternary alloys of iron, chromium, nickel, and silicon, in which the range of chromium is from 6 to 15 per cent., and the nickel 20 to 25 per cent., cannot be used in aircraft engine valves, since they cannot be hardened sufficiently to prevent excessive galling of the stems and wear on the tips. The ternary alloys of iron, chromium, and tungsten are not satisfactory on account of heavy scaling. Chromium steel is not satisfactory, as it loses its hardness at high temperatures, which causes a galling of that portion of the valve stems subjected to the action of the exhaust flame. Cobalt-chromium steel gives the best stem conditions, but has a tendency to scale and burn in the head, although not to the same degree as tungsten steels. It is satisfactory, except under unusual operating conditions. The ternary alloys of iron, silicon, and chromium satisfy the requirements of a valve steel in so far as the head and seat conditions are concerned, but they have the same drawback as the chromium steel in regard to softening of the stem in the section which is exposed to the action of the flame when the valve is open, but to a less degree.

F. A. Fahrenwald, *Principles underlying the Successful Use of Metals at High Temperatures* (Paper read before the American Society for Testing Materials, June 1924).

E. Pitois, *Classifying of Steels by Examination of the Grindstone Sparks in Air and in Oxygen* (Comptes Rendus, 1924, vol. 178, pp. 942-944). In the case of steels high in carbon and manganese, the sheaves of sparks thrown off on grinding in air are very brilliant. In an atmosphere of carbon dioxide, however, the sparks are reduced to a few dull red rays, from which it is concluded that the brilliance of the sparks in air is not due to mechanical heating alone. In oxygen, most steels give sparks of dazzling whiteness, while in air the same steels give red sparks, the sole exceptions being a few steels which are not oxidised even at high temperatures. If a sheet of glass is placed in the path of the sparks, incrustations are formed, and an examination of these shows that most of the particles produced by grinding ordinary

steels in air undergo fusion. The incrustations are partly pearlitic, but consist also largely of ferrite resulting from decarburisation, which is completed in an atmosphere of oxygen. The appearance of the sparks is influenced by the carbon content and is independent of any treatment which the steel may have undergone. The method is useful as a means of differentiation of tool steels and valve steels.

**Pyrometry.**—R. P. Brown, *Pyrometry, Past and Present* (Journal of the American Ceramic Society, August 1924, vol. 7, pp. 620–625). A brief review of the progress in pyrometry in the last fifteen years, and of the development of the use of pyrometers in the ceramic industries.

F. Henning, *The Determination of High Temperatures* (Zeitschrift für Elektrochemie, July 1924, vol. 30, pp. 309–318). A new form of optical pyrometer for the measurement of high temperatures by means of radiation is described. The chief characteristic of the pyrometer is that an image of the source to be measured, magnified five times, is formed at the filament of the standard lamp. These are both again magnified 4.5 times by means of an eye-piece lens, so that the source is magnified altogether 22.5 times. The standardisation of the instrument is described, and the temperature of the melting point of platinum is determined.

L. B. Haney, *The Principles and Applications of Thermo-Electric Pyrometry* (Proceedings of the Australasian Institute of Mining and Metallurgy, December 1923, No. 52, pp. 185–205). The principles, construction, and uses of the thermo-electric type of pyrometer are discussed.

J. N. Greenwood, *Determination of the Corrections to Optical Pyrometer Readings taken during Steel Making and Casting* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1923, vol. 12, pp. 27–74). In open-hearth working evidence was obtained that the optical pyrometer in use was giving low results. A calibration of the pyrometer was carried out on a black-body furnace. It was found that there is an average difference of approximately 40° C. between the apparent temperatures of flame and slag surface, and also there is an apparent fall of 30° C. when the flames clear from the hearth during a reversal. From the average of a large number of readings, it is concluded that if 32° C. be deducted from the temperature taken with gas on, the results will be the same as if luminous flames had been absent, in 88 per cent. of the cases. This correction has been found to hold for acid and basic charges at all stages of working.

F. E. Bash, *Characteristics of Some Materials for Base Metal Thermocouples* (Paper read before the American Society for Testing Materials, June 1924). The paper discusses the important considerations in choosing the elements of thermocouples, and presents the results of tests in which the thermo-electric properties of a number of alloys are determined against copper used as a standard material.

**Crystallography, Metallography, Constitution.**—National Physical Laboratory (*Report for the Year 1923*, London 1924). The work of the Metallurgy Department has been considerably extended during the year. In particular, the study of solid solutions and the structure of alloys has made good progress; much experimental evidence has been accumulated in favour of the theory of distortion of the space lattice when an atom of the solvent is replaced by an atom of a different metal. The study of the heat generated by plastic deformation has been advanced, and improvements have been introduced to secure greater accuracy of measurement.

J. F. T. Berliner, *Preparation and Properties of Pure Iron Alloys*.  
**IV. Determination of the Critical Ranges of Pure Iron-Carbon Alloys by the Thermoelectric Method** (Scientific Papers of the Bureau of Standards, 1924, No. 484). This paper is an extension of the work by Burgess and Scott. *Thermoelectric Measurement of the Critical Ranges of Pure Iron* (Scientific Paper No. 296). The apparatus and procedure were practically the same as in the previous work. The material used in the investigation was an exceptionally pure series of iron carbon alloys. Characteristic curves showing the changes in the thermoelectric properties of pure iron-carbon alloys are given for temperatures up to  $1150^{\circ}\text{C}$ . The A2 transformation was found to be constant at  $768^{\circ}\text{C}$ . for heating and cooling in all alloys having a carbon content up to 0.45 per cent., but it did not appear in alloys of a higher carbon concentration. The characteristics of the curves obtained indicate that the A2 transformation is of a different nature from the A1 and A3 transformations. The temperatures for the A3, A2, and A1 transformations are in fair agreement with those obtained by other methods. The upper end of the transformation is sharp; this is not the case when it is determined by other methods.

K. Honda, *On the Transformations in Pure Iron* (Transactions of the American Society for Steel Treating, August 1924, vol. 6. pp. 187–194).

K. Honda, *Carbon and Strain Effects on the Specific Heat of Carbon Steel* (Science Reports of the Tōhoku Imperial University, Sendai July 1924, vol. 12, pp. 347–358). The author has studied the variation of the specific heats of steels in the forged, annealed, and normalised states, in relation to the carbon present. The specific heat is not a linear function of the carbon concentration, but appears to be modified by the presence of stresses. It is concluded that the decrease of the specific heats of the steels examined, caused by prolonged annealing at  $650^{\circ}\text{C}$ ., is partly due to the release of the strain and partly to the decomposition of the cementite during the annealing. The fact that the specific heat of iron and steel is increased by strain is also applicable to other metals. Hence in an accurate determination of the specific heats of metals, they must at first be annealed at a definite temperature for a suitable interval of time and then their specific heats measured; otherwise the correct values cannot be obtained.

A high degree of strain in a metal is always accompanied by an internal or molecular disorder, which is equivalent to a small degree of freedom, and hence causes an increase of the specific heat.

O. V. Greene, *The Structure of Troostite and Sorbite* (Iron Age, September 11, 1924, vol. 114, pp. 615-617, 670). A number of photomicrographs are given showing the structure of sorbite and troostite in carbon steels. The steel used in the investigation had the following composition: Carbon 0.824, manganese 0.330, phosphorus 0.036, sulphur 0.014, and silicon 0.106 per cent. The steel was quenched and drawn at various temperatures. A modification of Archer's method was used for etching the specimens. By the use of this method present-day microscopes have sufficient resolving power at 1000 diameters to show the structure of troostite and sorbite.

F. Körber and W. Köster, *Granular Cementite* (Mitteilungen aus dem Kaiser-Wilhelm Institut für Eisenforschung, 1924, vol. 5, pp. 145-153). A study of the conditions under which granular cementite is formed.

E. Maurer, *Osmondite* (Stahl und Eisen, May 29, 1924, vol. 44, pp. 622-624). The term osmondite was first used by Heyn to designate a particular form of troostite produced by annealing steel containing 0.95 per cent. carbon at 400° C. The author describes the characteristics by which osmondite is distinguishable from hardening troostite, and points out that the difference between the two conditions is that osmondite is a structure produced by annealing and troostite is one produced by hardening.

K. Honda and T. Murakami, *On the Structural Constitution of Iron-Carbon Silicon Alloys* (Science Reports of the Tōhoku Imperial University, Sendai, January 1924, vol. 12, pp. 257-287; see also Journal of the Iron and Steel Institute, 1923, No. I. pp. 545-583).

A. Sauveur, *What is Iron, What is Steel?* (Chemical and Metallurgical Engineering, May 19, 1924, vol. 30, pp. 782-783). The following definitions are offered in the light of modern developments:

*Commercial Iron.*—Commercial iron is the element iron as pure as it can be commercially produced.

*Ingot Iron.*—Ingot iron is commercial iron which has been produced in a fluid condition and cast.

*Wrought Iron.*—Wrought iron is a ferrous metal which is malleable and which has been produced from a pasty condition.

*Steel.*—Steel is an alloy of iron and carbon, usually containing substantial quantities of manganese.

J. Czocharski, *Influence of Silicon and Iron on the Properties of Aluminium* (Zeitschrift für Metallkunde, May 1924, vol. 16, pp. 162-173). In rolling aluminium certain anomalies sometimes manifest themselves which appear to bear some relation to the proportion of iron silicide and silicon eutectic present in the metal. To investigate the matter, test-pieces of aluminium with varying contents of iron silicide and silicon eutectic were prepared and subjected to mechanical



tests and to a metallographic examination. It was found that a percentage of iron ranging from 0.59 to 1.42 per cent. had no deleterious effect on the aluminium. Above 2 per cent. iron the elongation diminishes by about 2 per cent. for every 1 per cent. increase of iron, the tensile strength remaining about the same. Silicon exercises proportionately the same effect, provided the percentage is kept within practicable limits. If the sum of iron and silicon amounts to 2 per cent. this proportion cannot be held responsible for inhomogeneity of the aluminium or for local defects which may appear in rolling. Only when irregular distribution of the iron and silicon in nests and zones or in patches on the surface occurs, do cracks and other defects manifest themselves.

H. C. Knerr, *Heat Treatment and Metallography of Steel* (Forging, Stamping, Heat-Treating, September 1924, vol. 10, pp. 319-321 *et seq.*). A series of articles forming a practical course on the treatment of steel and its structure and properties.

V. O. Homerberg, *The Macroscopic Examination of Steel* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 294-314). The method of preparing specimens for macroscopic examination, the formulæ for the etching reagents, together with directions for their use and the necessary precautions to be taken, are given. Macrographs are included in the paper to illustrate the results obtained from the use of the different reagents. The author also explains the manner in which segregation takes place in steel.

J. Durand, *New Macrographic Process for the Examination of Metals* (Génie Civil, August 9, 1924, vol. 85, pp. 131-133). The Baumann method of taking sulphur prints has certain disadvantages. Enlargements cannot be taken direct from the prints, because they are not transparent, and reproductions are not satisfactory on account of the coarse fibre of the paper, which blurs the details. The author proposes the use of photographic plates or films coated with bromide of silver which, when applied to a polished steel surface, give just as good prints as those obtained by the Baumann method, and when enlarged show the details with great clearness. These prints can be taken quite well by daylight or artificial light. They afford a means of comparing the sulphur content of only such steels in which the manganese content is about the same, as the manganese appears to have the effect of intensifying the impressions very considerably.

H. Schottky, *Note on Detection of Sulphur and Phosphorus by Metallographic Methods* (Kruppsche Monatshefte, June 1924, vol. 5, pp. 93-95). Sulphur prints taken across the grain of a plate of spring steel were blackened much more strongly than similar prints taken from a longitudinal section of the same plate, although analysis showed the sulphur to be evenly distributed throughout the material. The degree of discoloration does not, therefore, depend on the amount of sulphur actually present, but on the form and number of sulphide inclusions. Micrographs show that on a cross-section these appear as



numerous small spots close together, but the longitudinal section reveals them as short threads comparatively few in number. Considerable care is therefore necessary in using sulphur prints as a means of comparing the sulphur content of two steels. The direction of rolling or forging of a piece of steel can, however, readily be detected by taking prints of two surfaces at right angles to each other. Another agent which shows up strongly the direction of the fibre in a steel plate is Oberhoffer's etching medium, which brings out the primary structure of the material.

K. Harnecker and E. Rassow, *Etching Figures and Twin Formations in Iron* (Zeitschrift für Metallkunde, August 1924, vol. 16, pp. 312-314). A specimen cut from a steel boiler plate etched in nitric acid solution showed twin lamellæ, especially at those places where a slight deformation had occurred due to hammering, but whether the twinning was due to deformation or to recrystallisation could not be definitely determined. Another specimen of iron containing 1.3 per cent. phosphorus and 0.6 per cent. nickel, taken from a blast-furnace 'bear,' etched with ammonia persulphate, showed cubic figures in strong relief. The same specimen after stressing beyond the elastic limit showed twin bands in regular straight outlines. At larger magnifications etching figures of a star form appeared between the twin bands.

T. Ishiwara, *The Effect of Impurities on the Dendritic Structure in Carbon Steels, and their Diffusion at High Temperatures* (Science Reports of the Tôhoku Imperial University, Sendai, July 1924, vol. 12, pp. 309-332). The author has studied the effect of impurities on dendrites in steels; the diffusion of carbon, manganese, silicon, and phosphorus in iron, and the removal of dendrites by annealing at high temperatures; the effect of temperature on the diffusion of carbon in steels; and the reversed distribution of carbon in steel ingots. The diffusion velocity of carbon in iron increases very rapidly with the rise of temperature. The following formula holds good between 950° and 1300° C.:

$$v = e^c(t - t')$$

It was found that the existing theory of the reversed distribution of carbon in dendritic steels is not complete, and a new explanation has been added; the former theory is based on the ejecting action of phosphorus on carbon, while the present theory explains the same phenomenon by the separation of ferrite in the inter-dendritic boundaries. The reappearance of carbon-banding in a steel quenched and tempered is explained by the incompatibility of phosphorus and carbon.

K. Fischbeck, *The Ternary Diagram of Iron-Chromium-Carbon Alloys* (Stahl und Eisen, June 19, 1924, vol. 24, pp. 715-719). The author reviews the results of previous research work on the iron-chromium-carbon system, and, basing his observations on these, he has made a study of the process of solidification of iron-chromium-carbon alloys, and attempts to represent the system by means of a quaternary

diagram with the ordinates Fe,  $\text{Fe}_3\text{C}$ ,  $\text{Cr}_5\text{C}_2$ , and Cr. The  $\text{Fe}_3\text{C}$ - $\text{Cr}_5\text{C}_2$  and  $\text{Cr}_5\text{C}_2$ -Cr systems each show one eutectic point, and the Fe-Cr system two eutectic points and a maximum corresponding to the compound  $\text{CrFe}_2$ .

N. T. Belaiew, *The Granulation Hypothesis and the Delta-Gamma Change in Iron-Carbon and Iron-Nickel Alloys* (Transactions of the American Society for Steel Treating, June 1924, vol. 5, pp. 549-570). The author points out that the dendritic structure of alloys, as revealed by macro-etching, is a very stable structure and is not readily broken up during usual heat treatment operations. If the elements of secondary crystallisation, ferrite and cementite, lodge themselves according to the symmetry of the dendrites, a structure arises called the "structure of large crystals." This structure, when viewed by the unaided eye, shows a complete identity of picture with the dendritic structure. With the aid of the microscope the outstanding feature of this structure is the discontinuity of the excess element, ferrite or cementite, which has segregated into pseudo-dendrites or ferrite islets. This structure of large crystals occurs either in steels rich in carbon or in single crystals, and therefore is not of usual occurrence. The usual structure of steel articles slowly cooled is that of a network. Under the microscope this structure is characterised by the continuity of the mesh and by the continuity of the outer shell of the excess element around the inner nucleus. Based upon the investigations of the author and Giolitti, a discussion of castings and slowly cooled steels in relation to the structure of the dendrites is included. The author's granulation theory is described and discussed, and an explanation of the manner in which the delta-gamma transformation might account for the occurrence of granulation in alloys cooled down from the melt is given. A selected bibliography of literature on the subject is also appended to the paper.

J. H. Andrew and H. Hyman, *The Carbides in Nickel Chromium Steels* (Journal of the West of Scotland Iron and Steel Institute, Session 1923-24, vol. 31, pp. 116-123). The authors have investigated the character of the carbides in nickel-chromium steel in the quenched and tempered states. The following steels were used in the investigation :

Carbon.	Manganese.	Phosphorus.	Sulphur.	Silicon.	Nickel.	Chromium.
0.36	0.18	0.019	0.042	0.084	3.56	1.64
0.51	0.22	0.024	0.048	0.126	3.52	1.72
0.76	0.24	0.021	0.053	0.112	3.58	1.64
1.01	0.32	0.019	0.053	0.130	3.61	1.66

Carbides were separated and analysed in samples treated as follows : (1) Water quenched from  $770^\circ\text{C}$ . ; (2) water quenched from  $770^\circ\text{C}$ . and tempered at  $650^\circ\text{C}$ . for three hours ; (3) water quenched from

1200° C.; and (4) water quenched from 1200° C. and tempered at 650° C. for three hours. Detailed analyses of the carbides are tabulated. Nickel enters into the composition of the carbides in only very small amounts. The carbide recovered from steels quenched at 1200° C. and untempered was always of a very small quantity. The greater part of the residue was found to consist of finely divided carbon, the small quantity of combined carbon being almost entirely combined with the iron. Chromium merely existed as an impurity. An appreciable amount of carbide was recovered from steels quenched at 770° C. The existence of chromium carbide as such, in steels quenched at this temperature, is indicative of the fact that chromium carbide ( $\text{Cr}_3\text{C}_2$ ) is not completely decomposed on going into solution at the temperature of 770° C. Whether a prolonged soaking would bring about solution has not been determined. In the hypoeutectoid steels the chromium content is less in the tempered states than it is in the state quenched at 770° C. This may be attributed to the following reason:—It has been suggested that upon quenching at 770° C. a certain amount of chromium carbide is undecomposed, whereas carbide of iron has gone into solution and has probably been partially dissociated, thereby increasing the chromium content in the separated carbide. In the hypereutectoid steels the carbide of iron will not have gone into solution at the temperature of 770° C., and will accordingly show in excess in the analyses. The fact that, so far as can be ascertained from the steels experimented with, hypereutectoid carbide appears to be confined to carbide of iron, has suggested to the authors that the chromium carbide is not a constituent of the eutectoid.

V. N. Krivobok and O. E. Romig, *Surface Structure versus Inner Structure of Metals* (Transactions of the American Society for Steel Treating, July 1924, vol. 6, pp. 66-76). The authors discuss the structures which appear on the surface of cast metals and their relation to the inner crystalline structure of the metal. It is shown that the variety of structures appearing on the surface of cast metals is great, and may lead to erroneous conclusions regarding the grain size of the metal if care is not exercised in the examination of the specimen, since some of the observed marks are only surface phenomena.

F. C. Thompson and W. E. W. Millington, *The Effect of Free Surfaces on the Plastic Deformation of Certain Metals*. (This Journal, p. 61.)

H. Nagaoka and Y. Sugiura, *On the Regularity in the Distribution of Spectral Lines of Iron in Intra-Atomic Magnetic Field* (Japanese Journal of Physics, 1923, vol. 2, No. 1-2, pp. 1-52).

E. C. Bain, *The Application of X-Ray Crystal Analysis to Metallurgy* (Industrial and Engineering Chemistry, July 1924, vol. 16, pp. 692-698). The author describes the application of the Hull or Debye and Scherrer method to the study of the atomic arrangement of metals, and to the solution of such problems as the allotropy of iron, solid solutions, coring, grain-size effects, identification of new constituents, and the effect of cold-work on the orientation of grain

fragments. Examples of the results of research work in his own and other laboratories are quoted.

R. A. Patterson, *Crystal Analysis by the Diffraction of X-Rays* (Industrial and Engineering Chemistry, July 1924, vol. 16, pp. 689-691). Hull's method of applying X-ray diffraction to the analysis of crystals, especially those of metals, is expounded with the aid of diagrams. By this method it is possible to measure the distances between the different layers of atoms in the crystals, and by carrying it further to determine the arrangement of the atoms in the crystal.

W. P. Davey, *Application of X-Ray Crystal Analysis to Metallurgy* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 375-392). The paper outlines the methods used in applying X-ray crystal analysis to metallurgy, and gives some of the outstanding results so far obtained. Figures illustrating atom arrangements and a diagram of the method used in obtaining X-ray spectroscopic photographs are included.

R. Glocker, *Testing of Materials by Means of Röntgen Rays* (Zeitschrift für Metallkunde, May 1924, vol. 16, pp. 180-182). The interference method of the examination of materials by means of Röntgen rays is discussed. The investigation of the so-called fibre structure makes possible the determination of the orientation of the crystallites, and some new observations are recorded concerning the orientation of crystallites in electrolytically deposited metal sheets.

W. E. Williams, *The Application of X-Ray Analysis to the Study of Hardened Steel* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 175-195).

A. St. John, *X-Rays in the Foundry* (Paper read before the American Foundrymen's Association, October 1924). The use of X-rays for the examination of castings is dealt with.

**Corrosion Resistant Alloys.**—R. Stumper, *The Resistance of a Nickel-Chromium Steel to Corrosion* (Revue de Métallurgie, September 1923, vol. 20, pp. 620-621). An account of some experiments on the corrodibility of a chromium-nickel steel containing 15.68 per cent. of chromium and 7.04 per cent. of nickel. Simultaneous comparative tests were carried out with an ordinary mild steel, and in both cases the samples were exposed not only to ordinary acid corrosion, but to corrosion in acid baths activated by galvanic currents. The nickel-chromium steel showed extraordinary resisting properties, particularly in sulphuric acid solutions. With sulphuric acid solution containing 20 per cent. the corrosion of the chromium-nickel steel was only 0.5, taking the behaviour of the mild steel at 100. The highest rate of corrosion was in the case of a 20 per cent. hydrochloric acid solution.

W. H. Hatfield, *The "Stainless" Chromium Steels* (Paper read before the American Electrochemical Society, October 1924). The author discusses the influence of corroding media upon stainless steel. The presence of chromium when added to steel results in an increased



passivity in the presence of nitric acid; yet, on the other hand, the solubility in hydrochloric acid, and particularly in sulphuric acid, is increased in the case of the steel rich in chromium. There is evidence that the presence of chromium under strongly oxidising influence permits of the immediate modification of the surface of the metal in such a way as to produce complete passivity under certain conditions of temperature and concentration of the corroding media. The influence of the corroding media is readily modified by the presence of colloids. The reagents found to have little or no action on stainless steel and those which corrode stainless steel are given.

O. K. Parmiter, *Stainless Steel and Stainless Iron* (Transactions of the American Society for Steel Treating, September 1924, vol. 6, pp. 315-340). The author discusses the problems involved in the manufacture of stainless steel, its composition, and the influence of the various elements. The properties of this material—such as heat resistance, tensile properties, corrosion resistance, electrical conductivity and resistivity, magnetic properties, and thermal conductivity—are discussed. The microstructure, brazing and welding, cold-working, and machinery qualities are also dealt with. A brief discussion of stainless iron and its applications and possibilities is included.

C. E. MacQuigg *Some Engineering Applications of High Chromium-Iron Alloys* (Paper read before the American Society for Testing Materials, June 1924). The characteristics and applications of high chromium irons are discussed. Excellent castings are readily made throughout the range of carbon contents. Castings made in sand, as a rule, are easily machinable up to 1.5 per cent. carbon and may be made machinable by suitable heat treatment with as high as 3 per cent. carbon. Alloys with 20 to 30 per cent. chromium can also be forged, pressed, or rolled. The oxidation resistance of the high chromium iron alloys does not seem to depend upon any other factor to any such great extent as it depends upon the chromium content. Below 20 per cent., while the alloys are very much more resistant to oxidation than ordinary steels, they are noticeably inferior in oxidation resistance to alloys above 20 per cent. Alloys with about 26 to 28 per cent. chromium when exposed to oxidising atmospheres up to 1150° C., or higher, remain unaffected. Carbon monoxide and other reducing fumes and gases are without effect until very high temperatures are reached; however, above 1150° or 1200° C. such reducing atmospheres have a deteriorating effect on the alloys. The tensile properties of the alloys follow in a general way the same relationship to carbon as in steel and cast iron. Low carbon alloys are soft and ductile. The elastic limit in this class varies from 45,000 to 70,000 lbs. per square inch with corresponding tensile strengths of 75,000 to 90,000 lbs. per square inch. Ductility varies from zero to between 35 and 50 per cent. for elongation and reduction area. All these properties depend on the composition and heat treatment. With increase of carbon from 0.25 to 1 per cent. or more, the strength and



stiffness increase and tensile strengths run up to and well over 130,000 lbs. per square inch. Castings vary in tensile strength from 65,000 to 90,000 lbs. per square inch with low ductility. With 2.75 per cent. carbon the Brinell hardness of the sand-cast alloys may rise to 550 or 600 in the sand-cast condition, and are devoid of the brittleness which is found in white iron.

*Stainless Steel for Automobiles* (Automobile Engineer, July 1924, vol. 14, pp. 201-202). The properties and composition of stainless steels containing carbon percentages from 0.1 to over 0.5 are discussed, and the heat treatment of such steels is briefly described. Besides their corrosion resistant properties, their comparative strength at high temperatures renders them very suitable for certain parts of automobiles.

Miss C. Griff, *The Working of Stainless Steel* (Paper read before the Conference of Engineering Societies, Wembley: Foundry Trade Journal, September 25, 1924, vol. 30, p. 270). The paper deals with the commercial aspect of the use and working of stainless steel.

J. Strauss and J. W. Talley, *Stainless Steels, their Heat Treatment and Resistance to Sea-Water Corrosion* (Paper read before the American Society for Testing Materials, June 1924). The authors give the results of a study of the modification of physical properties of the corrosion-resistant steels by heat treatment and their behaviour when exposed to sea-water spray. The materials used in the experiments were arranged in the following groups:

- (1) Hardenable chromium steels.
- (2) Chromium steels that do not harden.
- (3) Steels in which the predominating alloying element is nickel.

Of the hardenable chromium steels, none of those studied is totally proof against the ravages of sea-water spray. Under conditions requiring hardness (for it is only in the hard state that considerable pitting can be avoided), but where a moderate accumulation of corrosion products is not objectionable, or where frequent cleaning of the parts is practicable, certain of the steels investigated are serviceable. A serious drawback to these high chromium alloys is the low proportional limit. For the hardening types, with the heat treatments used, the ratio of this value to the ultimate strength varies from approximately 0.4 to 0.7 except when using very high quenching temperatures; the value may then drop to 0.1 or lower. Higher values of the ratio are frequently found when employing tempering temperatures beyond 1000° F. For most purposes, hardening temperatures in the vicinity of 1900° F. are to be preferred as yielding the best combination of characteristics. For structural applications where a thin film of rust is acceptable, or where frequent cleaning is possible, all the steels of the second group may be satisfactorily employed. For the best results, steels with chromium under 15 per cent. must be heat-treated prior to use if the carbon content approaches 0.20 per cent. The nickel-chromium steels are applicable to the same classes of service as are

the steels of the second group. Normally, the proportional limit for these steels is very low; only in one case has it been appreciably raised by thermal treatment, cold-working being the only generally applicable method of raising it. The value usually varies from 20 to 50 per cent. of the tensile strength.

P. A. E. Armstrong, *Corrosion-Resistant Alloys* (Paper read before the American Society for Testing Materials, June 1924). A review is given of the metallurgical developments which have led up to the manufacture of chromium-bearing alloy steels with particular reference to the patent situation. Stress is laid upon the value of a 17 per cent. chromium steel containing about 1.50 per cent. silicon and under 0.10 per cent. carbon. The author also discusses the future effect of such alloys on the development of engineering construction.

R. J. Anderson and G. M. Enos, *Corrosion-Resisting Alloys for Use in Acid Mine Waters* (Paper read before the American Society for Testing Materials, June 1924). The nature of acid mine water from coal-mines is briefly discussed, typical analyses of such waters being given. The nature of the corrosion process is also dealt with. On the basis of various tests made, a list of materials which are resistant to acid mine waters has been incorporated in the paper, and the applicability of these materials to the construction of mining equipment is indicated.

*Symposium on Corrosion-Resistant, Heat-Resistant, and Electrical-Resistance Alloys—Introduction* (American Society for Testing Materials, June 1924, Preprint 19A). This report includes a list in tabular form of the commercial alloys manufactured in the United States, with the name of the manufacturer, the chemical and physical properties of the material and its principal applications. This tabulation forms a guide to engineers and users of these products in the selection of metals for specific uses.

**Corrosion.**—J. N. Friend, *The Relative Corrodibilities of Various Commercial Forms of Iron and Steel* (Second Report) (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1923, vol. 12, pp. 1–25). Specimens of wrought iron, carbon steels, and cast iron were subjected to various kinds of corrosion tests, with a view to studying their relative corrodibility. In general, there is a tendency for the corrodibility to rise with the carbon content, but in the neighbourhood of the eutectic point there is a break in the curve, followed by a fall in corrosion. The effect is more clearly seen in specimens with very low manganese.

J. N. Friend, *Recent Progress in the Study of Corrosion* (Journal of the Oil and Colour Chemists' Association, 1924, vol. 7, pp. 7–29, 48–50).

U. R. Evans, *The Corrosion of Metals* (Journal of the Oil and Colour Chemists' Association, 1923, vol. 6, pp. 150–154; 1924, vol. 7, pp. 29–32, 43–47).

C. H. Desch, *The Micro-Chemistry of Corrosion* (Paper read before

the American Electrochemical Society, October 1924). The theory of the process of corrosion is still in an unsatisfactory condition. The process is fundamentally electrolytic. Iron rust differs greatly from iron in electrolytic potential. The presence of colloids is not always essential to bring about corrosion. The author has made a microscopical study of the early stages of corrosion. A detailed description of the apparatus employed and of the method of testing alloys is given. Minute traces of foreign substances on the surface of the metal or alloy will often give rise to entirely different corrosion results.

W. G. Whitman and R. P. Russell, *The Submerged Corrosion of Iron* (Journal of Society of Chemical Industry, June 27, July 4, 1924, vol. 43, pp. 193-199T). The known facts, resulting from the observations of various investigators, concerning the corrosion of iron when submerged in ordinary natural waters, in alkaline waters, and in non-oxidising acids are enumerated. In explanation of these facts the general theory is propounded that the initial reaction in the submerged corrosion of iron is electrochemical and operates through a corrosion cell. At the anodic electrode of this cell the corroded metal sends ferrous ions into solution. A corresponding reduction occurs at the cathode area—usually the deposition of hydrogen ions as atomic hydrogen or the solution of dissolved oxygen to form hydroxide ions. Films of corrosion products exert a protective action which depends primarily upon the conditions attending their formation. Even the ordinary rust formed on iron by natural waters exhibits some degree of protectiveness, and certain waters build up more resistant layers than others. The solubility, density, and adherence of the rust film are very important factors. In alkaline solutions the reason for reduced corrosion is the greater film protectiveness due to decreased solubility of the rust. The effect of neutral salts in the water, while not yet fully understood, is undoubtedly attributable to their action on protective films. The protective film prevents effective electrolytic action between the outside of the rust and the metal, and as a result oxygen must diffuse underneath the surface of the rust film before electrolytic contact is established. Since the film protectiveness is maintained constant over the entire natural water range, the rate of corrosion in any given natural water is determined by the rate of oxygen diffusion alone. The composition and surface structure of the iron or steel are of practically no importance, and all commercial steels corrode at the same rate. Under alkalis the rate of corrosion decreases because the rust is more insoluble and forms a more protective film. In non-oxidising acids hydrogen gas is evolved and the rate of corrosion is largely affected by over-voltage. For this reason the composition and surface condition of the metal are important factors.

H. S. Rawdon and A. I. Krynsky, *Notes on Corrosion Testing by Different Immersion Tests* (Paper read before the American Electrochemical Society, October 1924). The need for choosing a corrosion test which shall in some measure approximate the service conditions

is emphasised and illustrated by reference to an unusual case of corrosion in a submarine cable. The general types of immersion tests, simple or total immersion, and two kinds of repeated immersion, continuous and intermittent, are described. Test results for a series of chromium steels in immersion tests of the simple and repeated type in distilled water, as well as immersion in dilute hydrochloric acid and citric acid are given. In general, the chromium steels are more resistant to the intermittent immersion than to simple immersion in distilled water—a phenomenon which appears to be associated with the formation of a protective film over the surface of the specimen.

U. R. Evans, *The Relation between Tarnishing and Corrosion* (Paper read before the American Electrochemical Society, October 1924). The paper describes investigations into the attack of gaseous sulphur dioxide on iron and zinc, and that of hydrogen sulphide on copper, with special reference to the part played by water in each case, and also the essential difference between tarnishing and corrosion proper. Iron and zinc are unattacked by dry sulphur dioxide, but a very small amount of water vapour is sufficient to allow the action to proceed apace. The surface of iron attacked by moist sulphur dioxide is dark, but is covered by tiny, bright circles with a dark spot, apparently a pit, at the centre of each. The interior of the pit is probably anodic, and the circular patch around probably owes its brightness to cathodic protection. In some cases rings of white crystals are seen arranged radially around the pits, evidently representing the corrosion product.

U. R. Evans, *The Corrosion Caused by Products of Combustion of Coal-Gas* (Journal of Society of Chemical Industry, May 16, 1924, vol. 43, pp. 506–507). A case is reported where corrosion was caused by the products of combustion of coal-gas. The corrosion occurred in a large room of a private house heated by two hot water radiators below which coal-gas was burnt direct, no provision being made for the removal of the products of combustion. After a few months the whole of the lower surface of the iron radiator was completely covered with a pale yellowish-brown incrustation which analysis showed to be mainly ferric sulphate (both normal and basic). The sides of the radiators were also covered with numerous scab-like growths of the same salt. The presence of sulphur dioxide in the fumes of the gas could alone account for the production of so much sulphate.

J. S. Vanick, *Deterioration of some Metals in Hot, Reducing Ammonia Gases* (Paper read before the American Society for Testing Materials, June 1924). The results are given of a study of a number of metals carried out in an endeavour to find the most suitable materials for nitrogen fixation equipment. Reducing gas mixtures of ammonia in nitrogen and hydrogen produce an intergranular fissuring in commercially pure iron, nickel, copper, and some of their alloys. Exposures of samples in the form of corrosion specimens, tension test specimens, or pressure bombs were made for periods as long as six months, to a



synthetising ammonia gas mixture at a temperature of  $500^{\circ}\text{C}$ . and a pressure of 100 atmospheres. Short exposures were also made to decomposing or "cracking ammonia." None of the metals except those exposed to the "cracking" ammonia was corroded in the sense in which corrosion is usually understood, namely, as a surface attack accompanied by disintegration or the formation of chemical compounds. Nearly all of the materials tested resisted corrosion successfully, with some advantage in favour of the non-ferrous group. Nearly all of the materials suffered a deterioration as measured by loss in mechanical properties such as tensile strength and ductility. For resistance to deterioration in a service requiring ability to sustain stress, as in heated bombs holding the gas mixtures under pressure, iron alloys of the type containing nickel, chromium, or aluminium seem to offer most resistance.

J. W. Shipley and I. R. McHaffie, *The Graphitic Softening of Cast Iron* (Industrial and Engineering Chemistry, June 1924, vol. 16, pp. 573-575). A study of the corrosion which takes the form of graphitic softening indicates that the destruction of the cast iron is due to an electro-chemical reaction set up within the structure of the iron. Probably the contiguous constituents of iron act as the poles of a miniature cell, the electrolyte being the water in contact with the iron. The tendency for iron to go into solution is greatest in ferrite and least in cementite. The series of constituents arranged in the order of this tendency is ferrite, pearlite, cementite-phosphide eutectic, and cementite. The potential difference between ferrite and graphite is about 0.56 volt, and when ferrite is adjacent to graphite this relatively high voltage is available for driving the iron into solution. Cementite and cementite-phosphide eutectic, being less subject to corrosion, form the residual skeleton structures. The resistance to corrosion of white cast iron in which the carbon is all combined and ferrite is absent, lies in the relatively low electromotive force existing between the constituents. The low solution pressure of the iron in these constituents also tends to prevent corrosion.

U. R. Evans, *A Paradox in Corrosion* (Chemical and Metallurgical Engineering, June 16, 1924, vol. 30, pp. 949-953). Former papers have shown that the corrosion of metals in chloride solutions in the presence of oxygen is electrochemical in character, being connected with the electric currents flowing between the aerated and unaerated parts of the surface; the unaerated (inaccessible) places become anodic, and attack becomes concentrated at these points, thus producing pitting or deep local corrosion. The present paper discusses the mechanism of the production of these currents. They might be due to one of two mechanisms:

- (1) The whole aerated area is ennobled by a thin protective film, so that the whole aerated area acts as cathode.

- (2) The "nobler" particles of the aerated area alone act as cathodes in the first instance.



*Corrosion—The Industrial Parasite* (Chemical and Metallurgical Engineering, July 14, 1924, vol. 31). This issue of this periodical is devoted to a series of articles dealing with corrosion problems of the various industries. The articles are as follows:

*How the Petroleum Industry is Solving its Corrosion Problems* (pp. 42–46).

*Combating Corrosion in Gas Manufacture* (pp. 47–50).

*Fertilizer Industry Conquering Corrosion* (pp. 50–51).

*How the Wood Distiller Dodges Corrosion* (pp. 52–53).

*Corrosion Problems in the Pulp Plant* (pp. 54–56).

*Food Products Fight Contamination* (pp. 56–58).

*Corrosion Dragon in the Sugar Industry* (pp. 58–60).

*Corrosion—The Constant Menace of the Chemical Industry* (pp. 61–69).

*How Metals stand up against Corrosion* (pp. 70–79). This article summarises the behaviour of pure metals and alloys under the action of the many destructive agencies encountered in the industries.

*Tabular Presentation of Chemical and Physical Properties of Corrosion-Resisting Alloys* (pp. 79–83). The principal chemical and physical properties of seventy-five corrosion- and heat-resisting alloys are tabulated.

D. V. Onslow, *A Critical Résumé of Information on Corrosion of Iron and Steel* (World Power, September 1924, vol. 2, pp. 146–155). A review of the work of previous investigators with special reference to the corrosion of cast iron.

H. S. Rawdon, A. I. Krynitsky, and W. H. Finkeldey, *Types of Apparatus used in Testing the Corrodibility of Metals* (Paper read before the American Society for Testing Materials, June 1924). A description of the various types of apparatus suitable for carrying out tests of the corrodibility of metals under different conditions. The different forms of apparatus described and illustrated cover the following tests: simple immersion, electrolytic, continuous repeated immersion, interrupted repeated immersion, mist or spray, and a simulated atmospheric test.

F. N. Speller and F. G. Harmon, *Electrolytic Theory of Corrosion* (Paper read before the American Electrochemical Society, October 1924). A discussion of the major points in an article on the same subject by W. D. Bancroft, published in the Journal of the Physical Society, August 1924.

R. J. Anderson and G. M. Enos, *An Accelerated Electrolytic Corrosion Test* (Paper read before the American Society for Testing Materials, June 1924). The authors give the results of experiments carried out in the development of an accelerated electrolytic corrosion test, in which forty-two metals and alloys were subjected to the accelerated test. Specimens of the same metals and alloys were also exposed to a long time immersion test in acid mine water, thus affording an opportunity for correlating the two types of tests.

F. H. Rhodes and E. B. Johnson, *Electrolytic Corrosion in a Water*

*Gas Holder* (Industrial and Engineering Chemistry, June 1924, vol. 16, p. 575). In the outer tank of a gas holder at a municipal gas plant, severe corrosion developed throughout a horizontal zone extending from about 4 inches to about 3 feet below the level of the sealing water. Investigation showed that the corrosion was not due to the simple rusting of the iron by dissolved oxygen in the water, nor to the chemical action of dissolved hydrogen sulphide on the iron, which would not have produced so large an amount of iron oxide in the scale. It was found that the corrosion was electrolytic in character, the difference in potential being produced by an oxidation-reduction cell. The water at the top of the holder contained some dissolved oxygen, and the iron shell in contact with this oxidising solution formed the cathode. The water some distance below the surface contained dissolved hydrogen-sulphide, so that the iron in contact with this solution formed the anode. The case is an unusual one, for the electrolysis is brought about by a single piece of metal being in contact with two solutions of different oxidising power instead of by two different metals in contact with each other in a single solution.

**Protection against Corrosion.**—J. N. Friend and B. L. Griffin, *The Protection of Iron with Paint against Sub-Aqueous Corrosion—Part II.* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1924, vol. 13, pp. 239–252).

E. Maas, *Protection of Metals* (Zeitschrift des Vereines Deutscher Ingenieure, August 23, 1924, vol. 68, pp. 880–883). In a lecture before the Government Commission on the protection of metals the author reviews the various theories of the corrosion of metals and the means adopted for its prevention.

R. Binaghi, *The Preservation and Protection of Iron from Corrosion* (Metallurgia Italiana, July 1924, vol. 16, pp. 299–310). The author presents a general review of the means in current use for the preservation of iron, and discusses the efficacy of paints, pigments, metallic coatings, oxidising and lacquering. A bibliography is given at the end of the article.

F. N. Speller, *Film Protection as a Factor in Corrosion* (Paper read before the American Electrochemical Society, October 1924). The natural protective coatings formed in water, air, and soils, and the factors influencing the character and deposition of protective films are discussed. Observations in the study of the corrosion of steel pipe led the author to undertake investigations which indicate that the use of silicate of soda has a marked effect on the rate of corrosion of iron in hot water, and a distinct but lesser effect on corrosion in cold water, without entirely stopping corrosion. The specific protection depends to some extent on the presence of other scale forming matter in the water, although protective films are formed with the use of sodium silicate in water even of zero hardness. In domestic use the addition of too much sodium silicate may give unpleasant results, when the

water is used for cooking purposes, because of excessive alkalinity. When the cost is not prohibitive, it is best to remove the source of the trouble, which in water corrosion is usually due to dissolved oxygen. However, the cost of deoxygenating water is at present prohibitive to many water supply systems, so that the best solution of the problem in such cases would seem to be to give the water the necessary amount of silicates to form a protecting film on the metal pipe.

H. C. Urquhart, *The Uses of Cadmium* (Proceedings of the Australasian Institute of Mining and Metallurgy, December 1923, No. 52, pp. 207-221). The use of cadmium as a protective coating is briefly dealt with.

J. N. Friend, D. W. Hammond, and G. W. Trobridge, *The Influence of Emulsoids upon the Rate of Solution of Iron* (Paper read before the American Electrochemical Society, October 1924). Emulsoids or protective colloids exert a very pronounced retarding influence upon the rate of corrosion of iron. The retardation is due to the adsorption of the emulsoid. Experiments are described which are thought to be of interest as suggesting a possible method of treating natural and other waters, to render them less corrosive towards ferrous and non-ferrous metals in practice. In these experiments small plates of steel were suspended in solutions of lead acetate, to which small measured quantities of agar were added. The results show a marked retarding action of the agar with rise in concentration. Other steel plates were suspended in solutions of copper sulphate, containing 0.05 per cent. of one of a series of emulsoids. Again the emulsoids showed a pronounced retarding influence. The deposition of copper on the surface of the plate affords only slight protection to the underlying metal. The corrosion loss increases with the temperature; the percentage retardation, due to the emulsoid, at first slightly rises with the temperature, but then falls. In dilute sulphuric acid and stationary plates, the retarding effect is readily detected. However, if the plates are rapidly rotated, little protective effect is observed. Iron cooking utensils resist corrosion remarkably well. This may be attributed in part to the protective action of the colloidal food material which is cooked in these utensils.

**Electro-Deposition.**—P. K. Frölich, *The Introduction of Carbonaceous Matter in Electro-Deposited Iron and Nickel* (Paper read before the American Electrochemical Society, October 1924). It has been definitely shown that carbonaceous matter may be found in electro-deposited iron and nickel, when there is not the slightest indication of any organic colloid in the electrolyte from which deposition takes place. Salts of organic acids or carbonaceous gases dissolved in the electrolyte are in many cases sufficient to account for the contamination of the deposited metal with carbonaceous matter. It is even possible to introduce such impurities into absolutely pure electro-deposits of iron and nickel, by exposing these deposits to cathodic

polarisation in solutions containing nothing but organic salts or carbonaceous gases plus a conductivity salt. The reactions responsible for the contamination are more or less dependent upon the nature of the inorganic ions discharged at the electrodes.

H. E. Haring, *Throwing Power, Cathode Potentials and Efficiencies in Nickel Deposition* (Paper read before the American Electrochemical Society, October 1924).

A. J. Allmand and A. N. Campbell, *The Electrodeposition of Manganese. Part II.* (Paper read before the Faraday Society, July 7, 1924). The best conditions for the electro-deposition of pure manganese consist in the electrolysis of a solution containing manganous and ammonium sulphates (the catholyte) separated by a diaphragm from the anolyte (ammonium sulphate solution), the H concentration being kept at  $10^{-6}$  to  $10^{-8}$  by the regulated addition, as required, of sulphuric acid or of ammonia. The temperature is  $30^{\circ}\text{C}$ . and the current density at the cathode 10–15 amps./d.m.<sup>2</sup>. The rotating aluminium cathode has a burnisher lightly pressing against it. Electrolyte manganese contains a considerable quantity of dissolved hydrogen, which is not, however, responsible for its brittle nature.

E. Liebreich, *The Electrolytic Plating of Metals with Chromium* (Zeitschrift für Metallkunde, May 1924, vol. 16, pp. 175–178). Certain properties of chromium render that metal eminently suitable for plating iron and steel articles. Its tendency to oxidise at high temperatures is very slight compared with other metals, and on account of this and of its high melting point of over  $1600^{\circ}\text{C}$ . it has been found useful for plating such objects as flat-irons, parts of lamps, cooking utensils, and electric welding machines. Another advantage of chromium is its great hardness; soft steel drawing dies, plated with chromium, are as effective as hardened steel dies, and such dies produce no sign of striation on the drawn material such as tubes, because the chromium coating takes an absolutely smooth polish. Some notes on the deposition of chromium are added, showing the improvements lately made in the process.

A. Günther-Schulze, *Coating of Aluminium by Electrolysis* (Zeitschrift für Metallkunde, May 1924, vol. 16, pp. 177–178).

**Metallurgical Education.**—S. L. Hoyt, *On Metallurgical Education* (Transactions of the American Society for Steel Treating, August 1924, vol. 6, pp. 195–202).



## CHEMICAL ANALYSIS.

**Analysis of Iron and Steel.**—A. Kling and A. Lassieur, *Typical Standards for Analyses* (Revue de Métallurgie, April 1924, vol. 21, pp. 247–254; Revue Universelle des Mines, January 1, 1924, vol. 1, pp. 53–54). An account of the formation and progress of a French Association to provide standardised steel samples. At a conference held in Paris in April 1923, an influential Committee was formed, which subsequently became incorporated as the Société des Échantillons-Types. The newly formed Association is pursuing its investigations and preparing standards in collaboration with the Bureau of Standards in Washington and with C. H. and N. D. Ridsdale. Particulars are given of the chemical tolerances allowed in the analyses. These tolerances are shown below :

	Per Cent.
Carbon . . . . .	$\pm 0\cdot03$
Silicon . . . . .	$\pm 0\cdot10$
Sulphur . . . . .	$\pm 0\cdot01$
Phosphorus . . . . .	$\pm 0\cdot008$
Manganese . . . . .	$\pm 0\cdot03$

An elaborate certificate is attached to the samples, and it is intended to make recommendations as to the analytical process approved for the particular elements. Two standards have already been prepared—namely, a basic open-hearth steel with 0·5 per cent. of carbon, and a basic Bessemer steel containing 0·05 per cent. of carbon. Each of these steels is, however, standardised in respect of silicon, sulphur, phosphorus, and manganese as well. In addition to the preparation of standard steels, it is intended to undertake the preparation of standard volumetric reagents, and later on to prepare standard tensile test-pieces and magnetic standards of permeability.

C. H. Ridsdale, *Engineers and the Interpretation of Chemical Specifications for Iron and Steel in Relation to Analytical Accuracy* (Proceedings of the Cleveland Institution of Engineers, Session 1923–24, No. 5, pp. 167–215).

W. E. Jominy, *Characteristics that Chemical Analyses Fail to Disclose in Pig Irons and Castings* (Paper read before the American Foundrymen's Association, October 1924). In order to determine whether or not cast irons of the same elemental chemical composition have the same or different characteristics when produced under varying blast-furnace and cupola conditions, the author has examined approximately one hundred samples of coke and charcoal irons. Transverse tests were made on test-bars and the standard tensile test was made on the lower half of each transverse specimen. Both Brinell and Rockwell hardness



tests were made on the transverse specimens near the fracture. Many of the samples were likewise subjected to a metallographic examination. The results show large differences in iron having the same chemical analysis, and that these differences persist throughout the remelting stage. The results support Johnson's contentions regarding the superiority of the charcoal irons. In addition, they show the variations of irons in strength, composition, and metallographic structure when produced in blast-furnaces under known widely variant conditions.

*The Analysis of Grey Iron Foundry Alloys* (Foundry Trade Journal, July 31, August 7, 21, September 11, 18, 25, October 2, 1924, vol. 30, pp. 89-91, 118-119, 165-166, 221-222, 250-251, 268-269, 290-291). A series of articles describing methods for the analysis of pig iron, ferro-silicon, spiegel, silico-spiegel, and ferro-manganese, which are applicable to grey iron foundry practice.

H. Burton-Smith, *Estimation of Carbon for Open-Hearth Bath Samples* (Iron and Coal Trades Review, July 4, 1924, vol. 109, p. 19). A method and apparatus employed for the estimation of carbon in bath samples are described. The method consists of burning the steel in the form of finely-sieved drillings in a silica or porcelain tube, passing a stream of oxygen through the tube in exactly the same manner as the ordinary dry combustion method, the only difference being that the gas is collected in a graduated burette and estimated volumetrically.

Persoz, *Estimation of Oxygen in Steel at the Knutange Works* (Revue de l'Industrie Minérale, Mémoires, September 15, 1924, pp. 466-468). Oxygen is a very deleterious impurity and in any considerable amount makes steel red-short and incapable of being rolled or forged. It is mostly present as FeO, a little being also in the form of MnO. Wrought and crucible steels do not dissolve oxygen. In the open-hearth and Bessemer steels it often occurs, and the only reason why it is not, as an ordinary matter of routine, estimated just as other impurities such as sulphur and phosphorus, is because most of the methods for its estimation are long, tedious, and uncertain. The new method is based on heating the drillings in pure hydrogen and absorbing the resulting water vapour in phosphoric anhydride. In these circumstances and at the temperature employed the whole of the FeO is decomposed, although the MnO is not affected. The pure hydrogen is produced by the electrolysis of a solution of potassium hydrate. An electric resistance furnace is used for burning of the sample, about 5 grammes of fine drillings being used, and heated to 1000° C. The sample is first exposed, in the apparatus, to a temperature of 500° C., which effectively disposes of any moisture, without affecting the result, as FeO does not decompose much below 1000° C. The following results are quoted:

	O per Cent.	FeO per Cent.
Basic steel . . . . .	0.041	= 0.180
Hard rail steel . . . . .	0.035	= 0.150
Tungsten steel . . . . .	0.022	= 0.099
A wild charge in which the blooms cracked on rolling . . . . .	0.190	= 0.850

T. E. Rooney, *The Estimation of Oxygen in Pure Iron* (this Journal, p. 122).

J. Vernay, *Estimation of Silicon in High-Speed Steels* (Chimie et Industrie, May 1924, vol. 11, pp. 886-888). Owing to the presence of chromium and tungsten the estimation of silicon in a high-speed steel becomes a lengthy and tedious business. In the presence of phosphoric acid, however, a complex but soluble phospho-tungstate is formed which enables the tungsten, which is so troublesome in the classic method, to be got rid of. The steel is digested in a covered porcelain capsule, with a phospho-sulphuric mixture, evaporated until dense white fumes appear, taken up with hydrochloric acid, and tartaric acid added. This helps to keep the tungsten in solution. The liquor is filtered and the residual silica washed, burned, and weighed. To ensure accuracy the silica should be volatilised by hydrofluoric acid, after weighing.

H. Dubovitz, *Determination of Silicon in Ferro-Silicon* (Zeitschrift für angewandte Chemie, 1924, vol. 37, p. 13). The method of decomposing Fe-C by heating with  $\text{Na}_2\text{CO}_3$ -MgO mixture involves danger to the platinum crucible, and the sample is seldom decomposed by only one fusion. The method proposed involves decomposition with NaOH or KOH solution in a nickel crucible.

T. Ashida, *Use of Zinc Amalgam in the Evolution Method for Determination of Sulphur in Iron and Steel* (Memoirs of the College of Science, Kyoto Imperial University, 1923, pp. 31-38).

L. A. Congdon and C. H. Belge, *Critical Investigations of Analytical Methods: Nickel* (Chemical News, 1924, vol. 128, pp. 67-68). The accuracy of the three usual methods for the determination of nickel is compared.

L. A. Congdon and R. K. Gurley, *Critical Investigations of Analytical Methods: Chromium* (Chemical News, 1924, vol. 128, pp. 68-70). Five methods for the determination of chromium were compared, the most accurate being the analysis using bichromate, iodine, and thiosulphate.

L. A. Congdon and J. L. Neal, jun., *Critical Investigations of Analytical Methods: Manganese* (Chemical News, 1924, vol. 128, pp. 70-71). A comparison is presented of the results of three methods for the determination of manganese.

L. A. Congdon and L. v. Rohner, *Critical Investigations of Analytical Methods: Molybdenum* (Chemical News, 1924, vol. 128, pp. 118-120). Four methods for the determination of molybdenum were tested and the results compared.

L. A. Congdon and T. H. Chen, *Critical Investigations of Analytical Methods: Cobalt* (Chemical News, 1924, vol. 128, pp. 132-134). Six quantitative methods for the determination of cobalt were tested as to their accuracy. Precipitation with  $\alpha$ -nitroso  $\alpha$ -naphthol proved to be the one that gave the most accurate results.

K. Swoboda, *Determination of Manganese by the Silver-Nitrate-Persulphate Method* (Zeitschrift für analytischen Chemie, 1924, vol. 64, pp. 156-184).

R. W. Coltman, *The Determination of Manganese* (Journal of Industrial and Engineering Chemistry, June 1924, vol. 16, pp. 606-609). Manganous oxalate is proposed as a primary standard in connection with the determination of manganese by Volhard's method, the chlorate method, and similar processes—its preparation, properties, and uses being described in detail. Among other things it is shown that the pure salt is best prepared from recrystallised potassium permanganate and oxalic acid, and that its use involves only a simple treatment of a weighed sample with nitric or sulphuric acid.

G. Tomarchio, *On the Estimation of Manganese in Metallurgical Materials Containing High Percentages* (Giornale di Chimica Industriale ed Applicata, April 1924, vol. 6, pp. 163-164). The sodium bismuthate method has recently been advocated for the estimation of manganese in rich alloys. It is, however, open to many objections. A modified Volhard-Wolff method, which is described, yields more generally accurate results.

A. Manuelli (Giornale di Chimica Industriale ed Applicata, April 1924, vol. 6, pp. 164-166) defends the accuracy of the Julian method, which employs titration with ferric nitrate and potassium permanganate solutions, and points out several sources of error in the Volhard method.

I. Musatti (Giornale di Chimica Industriale ed Applicata, May 1924, vol. 6, pp. 240-243) contrasts the various methods employed and considers the bismuthate method the safest.

O. Binder, *Technical Determination of Molybdenum* (Chemiker Zeitung, 1924, vol. 48, pp. 37-38). The generally used technical methods for the examination of the principal molybdenum products are described in detail.

K. Swoboda, *The Determination of Tungsten in Tungsten Steel* (Oesterreichische Chemiker-Zeitung, 1924, vol. 27, pp. 53-54).

G. Tomarchio, *Standardisation of Methods of Analysis in Metallurgy* (Metallurgia Italiana, July 1924, vol. 16, pp. 296-299). On account of the disagreement between analytical results obtained in different laboratories it has been proposed that the Society of Industrial Chemistry, Rome, should carry out tests of methods of analysis commonly in use, and recommend the adoption of a uniform practice in private and State laboratories. One leading chemist has proposed that for estimating manganese in high-grade alloys the bismuth-sodium method should be adopted. The author describes his own procedure in his laboratory at Savona, and maintains that the Volhard-Wolff method of estimating manganese is the quickest and most accurate one under any condition.

**Analysis of Ores.**—L. Brandt, *Volumetric Assay of Iron Ores by Means of Titanous Chloride* (Chemiker Zeitung, 1924, vol. 48, pp. 265-266, 270-271). The titanous chloride method of Knecht and Hibbert possesses the advantage over the usual volumetric methods of not requiring preliminary reduction of the iron to the ferrous state. It

was tested as to its applicability to the assay of iron ores, the tests bearing on the uniformity and proportionality of the results of the interference of other elements. Thiocyanate was used as internal indicator, being added either at the outset or after the bulk of the ferric salt had been reduced. The titrations were carried out at ordinary temperatures; it was found unnecessary to maintain an atmosphere of inert gas over the solution undergoing titration, but the stock solution of titanous chloride must be stored in a bottle communicating with a source of carbon dioxide; in this manner it keeps unchanged for several weeks. The process was found to be simple and accurate, and to give almost exactly proportional results. The only interfering metals are copper, antimony, vanadium, and platinum, whilst larger quantities of chromium and cobalt affect the end-point more or less by yielding coloured solutions. The interference of platinum (derived from the crucible in the case of bisulphate fusion) is smaller than in the permanganate titration. Antimony, cobalt, and vanadium occur very rarely and in negligible quantities; for practical purposes copper is the only metal which seriously interferes, being quantitatively reduced to the cuprous state.

W. W. Scott, *Diphenylamine Indicator in the Volumetric Determination of Iron* (Journal of the American Chemical Society, June 1924, vol. 46, pp. 1396-1398). Diphenylamine indicator, shown by Knop to be valuable in the titration of iron with potassium dichromate, may also be used in potassium permanganate titrations of iron. The presence of hydrochloric acid, stannic chloride, and mercurous chloride do not interfere, thus enabling potassium permanganate titrations to be made where formerly they were not possible.

A. Kling and A. Lassieur, *The Separation of Aluminium and Iron from Zinc, Manganese, and Nickel by the Acetate Method* (Comptes Rendus, 1924, vol. 178, pp. 1551-1552). The method gives accurate results in the separation of aluminium from zinc and manganese, but in the presence of iron the results are uncertain.

G. Carobbi, *Analytical Researches on the Traversella Scheelite* (Gazzetta Chimica Italiana, January 1924, vol. 54, pp. 59-63). Recent analyses have established the following approximate varieties of scheelite in the Traversella deposits and their composition:

	1.	2.	3.	4.
Tungstic acid ( $\text{WO}_3$ ) . . .	77.03	77.35	78.75	79.68
Molybdic acid ( $\text{MO}_3$ ) . . .	3.15	2.46	1.47	0.72
Lime . . . . .	19.73	18.33	19.23	19.43
Magnesia . . . . .	...	1.67	0.55	trace

The varieties tabulated are: (1) Colourless; (2) rose-brown; (3) greenish-brown; and (4) orange-yellow. The association of molybdic acid with the tungsten necessitates special care in the analysis of



the mineral, which is tedious and requires much time. A method is described which may be relied on to give the best results. A complete analysis recently carried out at the Chemical Institute in Naples has shown that niobium, tantalum, barium, strontium, and traces of lanthanum, cerium, and neo- and præsodymium are present.

E. Jünger, *Estimation of Tungsten in Low-Grade Ores* (Zeitschrift für analytische Chemie, 1923, vol. 63, pp. 438-439).

**Analysis of Coal and Coke.**—C. de la Condamine, *The Sampling of Coal* (Chaleur et Industrie, April 1924, vol. 5, pp. 189-194). A detailed consideration of the difficulties encountered in obtaining, from a large bulk of coal, a sample which shall be truly representative. The sources of error in sampling arise from the different sizes of the lumps and the different proportions existing between the lumps and the smalls complicated by the presence of stone and dirt. Formulæ are given showing how these factors influence the result.

H. Bahr, *Estimation of Sulphur in Coal* (Chemiker Zeitung, 1924, vol. 48, p. 428). The reliability of Eschka's method is questionable in the case of coals rich in sulphur (over 2 per cent.). The method proposed is based on the alumino-thermic reaction. A mixture of 0.5 gramme of coal, 0.4 of aluminium powder, and 3 of barium peroxide is briquetted; briquetting is indispensable to prevent loss by spirting. The briquette is ignited in a silica crucible covered with a perforated lid; all the sulphur present in the coal is converted into barium sulphide. After cooling, the crucible is treated in a suitable apparatus with dilute hydrochloric acid, and the hydrogen sulphide absorbed in cadmium solution, the sulphide being estimated with iodine and thiosulphate.

F. Bauriedel, *Sulphur Determination in Brown-Coal* (Chemiker Zeitung, 1924, vol. 48, pp. 122). The methods of Eschka, Brunck, and Langbein are compared for the determination of sulphur in brown-coal.

F. Foerster and J. Probst, *Determination of Sulphur in Coal and Coke* (Brennstoff-Chemie, 1923, vol. 4, pp. 357-358). The author shows the Eschka method to be incorrect in many cases, particularly with brown-coals.

H. H. Shepherd, *The Examination of Foundry Coke* (Metal Industry, September 12, 19, 1924, vol. 25, pp. 255-256, 283-284). The importance of the control of coke supplies in cupola melting is discussed, and an outline is given of methods for the sampling and analysis of coke.

**Analysis of Gas.**—H. Nielsen, *Gas Analysis: the Determination of Hydrogen and Methane in Producer-Gas* (Fuel, June 1924, vol. 3, pp. 204-205). The author describes a simple arrangement, embodied in a portable Orsat apparatus, which has been used for hydrogen and methane determinations, and has given results of considerably greater accuracy than the ordinary method.



## NOTICES OF RECENT BOOKS PRESENTED TO THE LIBRARY.

ASHTON, T. S. "*Iron and Steel in the Industrial Revolution.*" 8vo, pp. xi + 265. (Publications of the University of Manchester, No. clxiv.) London and New York: Longmans, Green & Co. (Price 15s. net.)

The author of this interesting history of a most important period in the development of the British iron industry is Senior Lecturer in Economics in the University of Manchester, and writes more from the point of view of an economist than of a regular historian. He has had access to sources of information which had either escaped the attention of, or have not been available to, earlier writers on economic history. The book consists mainly of an account of the growth and development of the production of iron and steel in England, Wales, and Scotland, within the period 1700 to 1815, based on the surviving records of business undertakings established in the eighteenth century, such as the Boulton and Watt Collection, the Coalbrookdale MSS., the Law Book of the Crowley Ironworks, the Horsehay MSS., the Huntsman MSS., the Thorncliffe MSS. of Newton Chambers & Co., Ltd., some old records of the Ebbw Vale Co., and the Minutes of the Meetings of Ironmasters.

The first chapter of the book sketches the growth of the charcoal iron industry and its position at the opening of the eighteenth century, the merits of Dud Dudley as pioneer in the use of coal for iron-smelting being placed in their proper perspective. In the following chapters is traced the development of the industry during the next 120 years, beginning with the first great discovery by Abraham Darby I. of the use of coke in the blast-furnace, which laid the foundation for all future advance. The author describes the part played by Boulton and Watt in introducing steam power, and the relations of that firm with John Wilkinson of Bersham, the Darbys of Coalbrookdale, the Carron Co., and other new undertakings, and shows how the steam-engine became a powerful auxiliary both in developing the industry and in stimulating the production of iron for the manufacture of the engines themselves. Benjamin Huntsman's invention of cast steel, together with Henry Cort's perfection of the puddling process and his invention of rolling bar iron which followed some years later, gave the crowning impetus to the establishment in Great Britain of an iron and steel industry on a large scale. The book closes with an account of the movements tending to combination among the ironmasters, and of the wages and conditions of labour in the latter half of the eighteenth century.

Not the least interesting passages of this history are those describing the vicissitudes of the industry due to political events of great moment, such as wars and revolutions. Much evidence is available to show that stagnation of the iron trade following a prolonged period of war is no new phenomenon, as may be seen from the account of the languishing state of the iron industry after the Seven Years War, and its complete prostration for several years immediately following the Napoleonic Wars.

BOUCHER, J. N. "*William Kelly : A True History of the so-called Bessemer Process.*" 8vo, pp. 258, illustrated. Greensburg, Pa., 1924 : The Author.

In this book the author attempts to revive the ancient controversy as to whom is due the main share of the credit for the invention of the Bessemer process. The respective merits of William Kelly and Henry Bessemer in the development of the pneumatic method of the refinement of molten pig iron have long ago been assigned their true place in history, and those interested in searching into the matter for themselves can consult such eminent and impartial authorities as James Swank, Lyman Holley, and Dr. Rossiter Raymond. In fact, it is common knowledge that Kelly in 1856 established his claim to priority over Bessemer in the invention and use in the United States of the pneumatic process. The fantastic story told by the author, in which he seeks to show up Bessemer as a mere charlatan who pirated Kelly's invention by unworthy means, is not supported by a shred of trustworthy evidence. It is remarkable chiefly for the manifestation of envy of Bessemer who achieved a brilliant success, whereas Kelly, who had begun groping along the same lines a year or two before Bessemer started his independent experiments, met with comparative failure. Unconsciously, perhaps, the author has thrown sufficient light on the state of mind of William Kelly, at the time he realised that Bessemer had conceived a more effective means than his own for carrying out the process of refining iron, to show that the whole story of Bessemer's alleged visit to Kelly's furnaces at Suwannee for the purpose of pirating Kelly's invention was nothing more than an inspiration of the overwrought imagination of a disappointed man. Obviously the story must have been made public at the time, *i.e.* about 1857, if its originator had had a genuine belief in his own allegations:

EVANS, U. R. "*The Corrosion of Metals.*" 8vo, pp. xii + 212, illustrated. London, 1924 : Edward Arnold & Co. (Price 14s. net.)

In this work the author has sought to emphasise the essential mechanism of the changes in metals due to corrosion, choosing examples from industrial or engineering practice to illustrate the manner in which the different factors operate. Throughout the volume abstruse mathematics are almost entirely avoided; in a few places, where a more detailed description of some matter involving symbolism has seemed desirable, the necessary treatment has been compressed into a footnote. The book opens with an historical survey of the subject, and a chapter is devoted to information in a condensed form concerning certain elementary facts of electrochemistry. A certain amount of experimental work has been undertaken specially for the purposes of this book, and the results are published in it for the first time. In view of the magnitude of the subject and the brief space available, numerous references are given in footnotes to literature, where fuller details of particular sections of the subject can be found. In the body of the book examples are given of different types of corrosion, sometimes of one metal, sometimes of another, therefore it has been thought well to add an Appendix, in which the individual metals are discussed in turn. Here the behaviour of each metal towards the most important corrosive agencies is summarised very briefly, and, in contrast with earlier chapters, no attempt is made to suggest causes for the facts enumerated.

The work is a valuable addition to the literature on the subject.

GREAVES, R. H., and H. WRIGHTSON. "*Practical Microscopical Metallography.*" La. 8vo, pp. x + 125, with 184 figures. London, 1924 : Chapman & Hall, Ltd. (Price 16s. net.)

Both the authors of this work are of the Research Department, Woolwich. The book is intended to provide, within a small compass, a set of

typical photomicrographs, suitably annotated, and accompanied by an account of such related matters as might profitably occupy the minds of students devoted to microscopical work. In this work the structures of metals and alloys of industrial importance are considered in detail in the light of their construction, but with special reference to their mechanical properties and practical utility. A description is also given of the technique of microscopical examination and of photomicrography; and methods of overcoming some practical difficulties which may be encountered are indicated. The book contains the following chapters: I. Introduction; II. Preparation of Specimens for Micro-Examination; III. The Microscope and Method of Microscopical Examination; IV. The Structure of Pure Metals and of Alloys; V. The Structure and Properties of Ingot Iron and Wrought Iron; VI. The Structure and Properties of Normalised and Annealed Carbon Steels, and the Effect of Hot and Cold Work; VII. The Structure and Properties of Hardened and Tempered Carbon Steels; VIII. The Structure and Properties of Alloy Steels, and the Effect of Heat Treatment; IX. Non-Metallic Inclusions and Defects in Steel; X. The Structure and Properties of Pig Iron, Cast Iron, and Malleable Cast Iron; XI. The Effect of Impurities in Copper; XII. The Structure and Properties of Alloys of Copper with Zinc, Tin, and Aluminium; XIII. The Structure of Aluminium Alloys, Zinc Alloys, and Bearing Metals.

The book should be of great value to those who desire to make use of this method of examination.

JOHANNSEN, O. "*Geschichte des Eisens.*" 4to, pp. 246. Compiled in collaboration with others, under the auspices and at the instance of the Verein Deutscher Eisenhüttenleute. Düsseldorf, 1924: Verlag Stahleisen, M.b.H.

To quote the opening words of the Preface of this book: "Just as the voyager through uncharted seas must preserve a precise knowledge of the course already traversed in order to determine his present position and set his future course, so the craftsman must study the records of the past concerning his craft if he desires to co-operate in building up the noble edifice of modern technical achievement. From a sound knowledge of history, youth may gain the experience and judgment of age." The object of the work is accordingly to present within a reasonable compass a succinct account of the history of iron, from the earliest ages down to the end of the nineteenth century, based mainly on the well-known monumental work of Dr. Ludwig Beck, with additional matter derived from sources which have come to light since Dr. Beck's day. The book divides the history of iron into four periods: The primitive period, up to about the time of the great migration of nations; the Middle Age, ending about the year 1500, when the manufacture of iron was revolutionised by the invention of the blast-furnace; the later Age, or the age of the charcoal blast-furnace, which came to an end in the various iron-producing countries at different dates between 1750 and 1850; and, finally, the Age of Coal, which is subdivided into the age of malleable iron and the age of low carbon steel made by a fusion process. An interesting illustration is the reproduction of an ancient document dating at the end of the fourteenth century, which contains the first authentic written record of an ironfounder, one Merckeln Gast of Frankfort, who claims, among a number of other accomplishments, that he can cast small iron cannon and firearms. The document is now preserved in the archives of the city of Frankfort. The history of the rise of the iron industry in England, due to the discovery of Abraham Darby of the use of coke for smelting pig iron in the blast-furnace, is dealt with at some length and is exceedingly well told; indeed, throughout the period and right to the end of the nineteenth century, which is about as

far as the author takes us, the events are recorded with great regard to accuracy and impartiality. The illustrations are excellently reproduced, and in general style and make up the book leaves nothing to be desired.

KOREVAAR, A. "*Combustion in the Gas-Producer and the Blast-Furnace: A New Theory.*" 8vo, pp. xii + 177, illustrated. London, 1924: Crosby Lockwood & Son. (Price 15s. net.)

After devoting some years to the study of the theory of the blast-furnace, the author, who holds the position of Lecturer in Industrial Chemistry at the University of Leyden, has found that the ordinary principles of combustion furnished no adequate explanation of certain phenomena observed in the practical working of a blast-furnace, and to account for these it became necessary to establish a new theory of combustion. To begin with, a blast-furnace is considered to have two functions—namely, the production of heat, which is termed "the producer function," and the reduction of the iron from the ore, which forms "the metallurgical function" of the furnace. The producer function involves the combustion of coke as carried out in the producer, and accordingly the author, before proceeding to elaborate his new blast-furnace theory, presents a theory of combustion as it takes place in the gas-producer, the efficiency of which depends entirely upon the state of its zone of combustion. It is shown that the factors that govern the temperature of the zone of combustion of the gas-producer are the same as those that dominate in the zone of combustion of the blast-furnace, and these are: the carbon factors (combustibility), the air factors (velocity, temperature, moisture), and the furnace factors (diameter and conductivity of furnace walls). A consideration of the influence of the carbon factors on the volume of the zone of combustion leads to the formulation of the "law of heat compression," which forms the basis of the author's new theory of combustion. Briefly, it is shown that by use of coke of a higher combustibility the zone of combustion is reduced in area, but is raised considerably in temperature, or, as the author puts it, the heat becomes "compressed," owing to the smaller space in which it is generated, the heat losses being consequently reduced, and considerable fuel economy results.

In Part II. of the book this theory is applied to blast-furnace practice, and it is shown that the fuel economy gained by means of the use of fuel of high combustibility, hot-blast, and other factors governing combustion, is all due to the law of heat compression.

The book, as the author admits, is somewhat abstruse, but nevertheless it forms a valuable contribution to our knowledge of the theory of the blast-furnace. The English rendering of the text might be improved on, and even the law itself on which the new theory of combustion is raised might better have been termed: "The law of heat concentration." In issuing a second edition the author would be well advised to submit the text to an expert in blast-furnace practice for correction of some minor defects in the use of technical terms.

"*Physics in Industry.*" Lectures delivered before the Institute of Physics. 8vo. Vol. I. pp. 59, with a Foreword by Sir J. J. Thomson, O.M., F.R.S. Vol. II. pp. 48, with a Foreword by the Hon. Sir Chas. A. Parsons, K.C.B., LL.D., F.R.S. Oxford, 1924: Oxford University Press. London: Humphrey Milford. (Price Vol. I. 2s. 6d. net; Vol. II. 3s. net.)

These volumes contain a series of six lectures, which have been delivered before the Institute of Physics, on the part played by physics in various industries. To judge from the experience of the past, no method is more likely to lead to increased production than the industrial application of



physical science and the results of research. To do something to promote this is one of the objects of these lectures. The contents of Volume I. are: Physics in Engineering Science, with Special Reference to Mechanical Engineer, by Professor Archibald Barr, D.Sc.; The Physicist in Engineering Practice, by Sir James A. Ewing, K.C.B., F.R.S.; The Physicist in Electrical Engineering, by C. C. Paterson, O.B.E. Volume II. contains the following lectures: Applications of Physics to the Ceramic Industries, by J. W. Mellor, D.Sc.; The Physicist in the Textile Industries, by A. E. Oxley, D.Sc.; The Physicist in Metallurgy, by C. H. Desch, D.Sc., F.R.S.

SACHS, G. "*Grundbegriffe der Mechanischen Technologie der Metalle.*" 8vo, pp. 317, with 232 figures in the text. [The work forms Vol. II. of the series "*Der Metallische Werkstoff*," edited by W. Guertler.] Leipzig, 1925: Akademische Verlagsgesellschaft M.b.H. (Price 15 marks.)

This book deals mainly with the nature and character of the changes in properties and structure which manifest themselves in metals as the result of mechanical treatment, particular consideration being given to the laws governing the permanent deformation of metals due to applied stresses. In the first part of the book the relations between the stresses and the nature of the deformation produced by these are discussed. The second part treats of the behaviour of metallic crystals and of crystalline aggregates so far as light has been thrown on this subject by the study of single crystals. Finally, in the third part, consideration is given to the relationship between the structure of pure metals and alloys, and their mechanical properties, the influence of heat treatment being also briefly referred to.

The author has made a critical survey of the work of other investigators, and has collected and summed up in this book practically the whole of the available knowledge upon the subject of the manner in which the mechanical properties are affected by stressing metals in various ways, such as by cold-working, and by the application of tensile, compressive, and torsional forces, and of the extent to which these properties are revealed by the various methods of testing. By comparing the main results of the different experts, he has aimed at harmonising many apparently contradictory phenomena which manifest themselves as the consequence of cold-working, and he establishes that a definite knowledge of the mechanical treatment which a material has undergone is, in general, sufficient to enable the engineer to judge the value of the mechanical properties, concerning which it is necessary to have accurate knowledge for the purposes of his calculations.

A vast amount of research on the effect of cold-working has been carried out in the last ten or twelve years, but the author is probably the first to have collected the main results of the work of numerous experts in different countries, and to have made these available within the compass of a single book. Such a work must therefore be a valuable acquisition, not only to metallurgists, who have to supply materials of construction, but also to engineers and designers of machines and structural work. A good translation of the book into English would be highly useful.

SKELTON, H. J. "*Economics of Iron and Steel: Being an Exposition of Everyday Practice in the Heavy Iron and Steel Trades.*" 8vo, pp. 679. Second edition. London, 1924: Stevens & Sons, Ltd., and H. J. Skelton & Co., Ltd. (Price £1.)

The book sets forth the leading principles and practices of the British iron and steel trades, more particularly in the heavy manufacturing trades, which the average engineer, merchant, buyer, and user ought to know and understand. The information presented has been acquired by the author



in the course of a busy life in intimate association with the iron and steel industry, and as head of a firm of buyers of iron and steel of diverse origin and for various purposes at home and abroad. The nature and composition of the ores and other raw materials used, and of the products obtained from the various processes, are set out in full, and an extremely useful feature of the book is the enumeration and definition of the principal brands and classes of pig iron, wrought iron, and steel, with details of their manufactures and analyses, supplemented by a good glossary. The standard tests for steel material, and also the standard dimensions of rolled products as prescribed by the British Engineering Standards Association, are given. A chapter is devoted to an exposition of the conditions of sale customarily observed by British manufacturers, followed by a comparison with sales conditions prevailing on the Continent, and much other information of a highly practical and useful nature has been brought within the compass of the book.

In view of the publications which are continually appearing in other countries presenting an up-to-date picture of the economic position of their respective national iron industries, it has been somewhat of a reflection on the British iron industry that no really authoritative work on that industry has been published for many years, and the gratitude of British manufacturers is certainly due to the author for the timely appearance of this handbook, which supplies a serious want of long standing.

“*Taschenbuch für Berg- und Hüttenleute.*” 8vo, pp. 1477, with 810 figures in the text. Edited by F. Kögler, with the collaboration of the following authorities: G. Brion, A. Brosche, O. Dahlke, A. Dannenberg, G. Franke, A. Gerke, W. Gross, R. Hoffmann, W. Hüttner, K. Kegel, F. Kögler, F. Kolbeck, K. Krug, H. Neumann, H. Niess, F. Peters, C. Schiffner, F. Schulte, F. Schumacher, A. Schwemann, F. Seidenschnur, G. Spackeler, E. Treptow, A. Wallich, E. Wandhoff, and W. Weigelt. Berlin, 1924: Wilhelm Ernst u. Sohn. (Price 25s.)

This new pocket-book forms a complete and up-to-date compendium in thirty-two chapters of the art of mining and mine-surveying, and of the subsidiary branches of technology related to the winning of minerals, their treatment and preparation, and the extraction of metals from the ores. As introductory to the main subject of the work, the first three chapters contain respectively concise expositions of the science of mineralogy, practical geology, and the theory of mineral deposits, this last-named subject being divided into the following sub-sections: (1) Ore deposits—their formation, structure, composition, and classification; (2) Salt deposits, such as rock-salt and potash deposits—their origin and structure; (3) the Coal measures—the origin and classification of coal, and brown-coal deposits; (4) Petroleum deposits—their geology, origin, and the occurrence of petroleum. Then follow chapters dealing *seriatim* with every operation involved in the opening and development of mines, methods of working, surveying, equipment, the washing, briquetting, and coking of coals, ore-dressing and extraction of the metals from their ores, assaying, and other subjects, not omitting a review of mining law.

The work is not intended to form a text-book, but to serve as a comprehensive book of reference for the benefit of those engaged in or interested in mining and metallurgy generally, or in any one branch of those arts. Each chapter on every separate subject has been specially compiled by an authority with expert knowledge of that particular subject. A wealth of information is given concerning methods, appliances, outputs, and costs, all of which is based on absolutely up-to-date practical experience, though owing to conditions which vary from one district to another, the values

given by a writer with special experience of the conditions in one district only, must in some cases be regarded as rough average values only. This is particularly the case as regards the section dealing with Metallurgy, in which industry, furnaces, ores, fuels, processes, and methods of working differ very widely. It should be added that a short bibliography of standard works on a subject is given at the head of each chapter dealing with that subject.

The work certainly fulfils all that the editor claims for it, as a valuable work of reference. Notwithstanding his disclaimer of its purpose as a text-book, it might likewise quite well serve on occasion as a most useful text-book for advanced students, as well as for professional mining engineers and inspectors.

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[References to the papers read before the Institute are indicated by the word *Paper* following the page number. The letter *P.* denotes a reference to a subject incidentally mentioned in a paper. The letters *D.* and *A.* denote references to discussions on papers and to the section dealing with abstracts respectively.]

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